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# Electrotechnology Applications for Potable Water Production And Protection of the Environment

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## Legal Notice

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# Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER program, managed by the Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for the Electrotechnology Applications for Potable Water Production and Protection of the Environment, contract No. 500-97-044 under the project management of Southern California Edison and conducted by a consortium of researchers from the Metropolitan Water District of Southern California, Orange County Water District, and the Electric Power Research Institute. The report is entitled "Electrotechnology Applications for Potable Water Production and Protection of the Environment." This project contributes to the Industrial/Agricultural/Water End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: <http://www.energy.ca.gov/pier/reports.html> or contact the Commission's Publications Unit at 916-654-5200.

# Executive summary

Southern California with its sixteen million residents and a dynamic $450 billion regional economy depend on a reliable and affordable supply of potable water. Most of the current supply is imported from Northern California or the Colorado River. Water transfer from the north requires significant energy for pumping and major disturbance to the environment

This study focused on the development of alternative water source and using electrotechnologies that could significantly reduce energy use and minimize environmental problems. Six innovative water/wastewater treatment process technologies were researched and evaluated. Eight specific tasks were developed to address the study objectives. They are:

- Advanced oxidation processes
- Biological denitrification
- Solids removal technologies
- Salinity removal technologies
- Disinfection alternatives
- Solid processing techniques
- Energy and process assessment
- Technology transfer and process scale-up for commercial deployment

The following is a summary discussion of these tasks relative to task objectives, outcomes, conclusions, recommendations and benefits to California.

*Task 2.1 - Investigate Advanced oxidation Processes*

**Objective**

Study the effectiveness of Pulse UV for the reduction of bromate, MTBE, NDMA, perchlorate, and taste & odor.

**Outcomes**

1) Bromate reduction by Pulsed UV – no significant reduction in bromate at UV doses less than 100 mJ/cm$^2$. When compared to the UV for 1-log$_{10}$ inactivation of Cryptosporidium, Pulsed UV takes almost 1000 times UV dose for the same reduction of bromate.

2) MTBE reduction by Pulsed UV and ozone/peroxide – without $H_2O_2$, a high UV dose (47,000 mJ/cm$^2$) reduced MTBE by 87 percent; adding 69 mg/L $H_2O_2$ lowered the required dose to 1600 mJ/cm$^2$. These UV and $H_2O_2$ doses, however, are prohibitive in drinking water applications. At high MTBE concentration (2000μg/L), Ozone/peroxide (PEROXONE) removed substantially more MBTE than ozone alone. However, at the lower MBTE concentration (200 μg/L), ozone and PEROXONE performed similarly.

3) NDMA treatment by Pulsed UV and ozone/peroxide – $H_2O_2$ addition did not improve NDMA removal. However, water quality parameters such as nitrate and turbidity presence could affect NDMA removal. Reduction of NDMA by

ozone (at 5 mg/L) was minimal but was much greater (50%) with PEROXONE at the same concentration.

4) Perchlorate reduction by Pulsed UV – no measurable perchlorate reduction was observed because perchlorate does not absorb UV light.

5) Taste and odor reduction by Pulsed UV –Without $H_2O_2$, 10,100 mJ/cm$^2$ applied UV (very high) dose was needed to reduce MIB and geosmin by 92 and 97 percent respectively. Adding 5.5 mg/L of $H_2O_2$, only 1,100 mJ/cm$^2$ was needed to achieve comparable results.

**Conclusions**

1) Bromate reduction by Pulsed UV

- Bromate reduction was more efficient in laboratory waters (89 %) than natural waters (18%) for UV dose of 3,100 mJ/cm$^2$ and 4,000 mJ/cm$^2$ respectively

2a) MTBE reduction by Pulsed UV

- UV alone cannot effectively reduce MTBE
- UV/$H_2O_2$ is effective in reducing MTBE
- $H_2O_2$ dose strongly affects efficiency of MTBE reduction

2b) MTBE reduction by Ozone and PEROXONE

- PEROXONE was more effective in oxidizing MTBE than ozone, particularly when water contained higher MTBE concentrations
- Ozone doses of 19 mg/L (with 47 mg/L $H_2O_2$) and 24 mg/L (with 30 mg/L $H_2O_2$) were needed to meet the secondary standard of 5 µg/L for 200 and 2,000 µg/L of MTBE, respectively;
- MTBE by-products such as TBF, TBA, acetone, and aldehydes were identified to have hindered MTBE removal efficiency

3a) NDMA Reduction by Pulsed UV

- UV alone is effective in removing NDMA
- Characteristics of water type played an important role for NDMA reduction
- NDMA removal was affected by a strong competition for UV light absorption between NDMA and background organics (e.g., TOC and $UV_{254}$-absorbing organics) and nitrate

3b) NDMA reduction by Ozone and PEROXONE

- Ozone alone is ineffective in NDMA reduction in drinking water
- PEROXONE improved NDMA removal efficiency compared to ozone alone

4) Perchlorate reduction by Pulsed UV

- Perchlorate was not reduced by UV

- Perchlorate concentration, $H_2O_2$ dose and pH had no effect on perchlorate reduction

5) Taste-and-Odor Compounds

- A UV dose of 10,100 mJ/cm$^2$ reduced MIB and geosmin by 92 and 97 percent, respectively
- 100 mJ/cm$^2$ (a disinfection-level UV dose) and 5 mg/L $H_2O_2$ provided 86 and 96 percent reduction of MIB and geosmin, respectively.

**Recommendations**

Based on water quality issues and cost requirements, one of the technologies evaluated here could be applied for reduction of water contaminants. Although ozone may be significantly less energy-intensive than UV for several of the micropollutants studied, UV may be a more appropriate option based on DBP formation potential. In considering these technologies, utilities must weigh energy and DBP costs prior to implementation.

**Benefits to California**

It is beneficial for California utilities to understand the limitations of advanced treatment techniques before implementation. As UV light may provide excellent disinfection efficiency and low DBP formation at disinfection-level dosages, high energy requirements for micropollutants treatment may cause water utilities to consider ozone. Utilities must, however, consider the level of DBPs that high ozone dosages may produce.

*Task 2.2 – Biological Denitrification*

## Objectives

- Demonstrate the technically and economically viability of biological denitrification
- Obtain California DHS approval for the *BioDen™* system as a viable treatment system for nitrate removal and potable water production
- Demonstrate ceramic filtration is a viable post treatment for biological denitrification
- Determine O&M costs for biological denitrification unit using hollow fiber microfilter, including power consumption and methods to reduce power requirements.

**Outcomes**

In 1995, the City of Modesto purchased the Grayson water system from Del Este. The water supply is valuable to the City, but the water is contaminated with excess nitrates. The City was interested in assessing biological denitrification as a low-cost option to the more conventional treatment possibilities. Significant progress was made in implementing the demonstration project described in this report. However, at the end of 2000 the City decided to delay the commercial demonstration project in favor of drilling a new 1,000 feet deep well to obtain water with nitrates below the regulatory action level. EPRI and the researchers would like to see the demonstration project be launched in the next three to six months.

**Conclusions**

- On December 20, 2000, the City of Modesto officially notified the researchers at Nitrate Removal Technology of its decision to postpone the Grayson Biological Denitrification Project. Instead, the City would install a 1,000 feet deep-well in the area of the Grayson system to obtain water with nitrate below the government action level. The City staff was extremely reluctant to use microbes to accomplish a potable water treatment goal, even with post disinfection of the effluent. This potential health concern was the road block that must be overcome before the technology can be commercialized.
- While EPRI and the researchers were disappointed with the City's decision, the team was able to secure approval from the California Department of Health Services for a suitable test protocol for this process. As designed, the protocol will yield valuable information for the Department to rule on the efficacy of the biological denitrification treatment system.
- Based on discussions with California DHS and other interested parties, the Modesto pilot study will be conducted in two phases. The first phase will consist of a one to three-month demonstration of a 6 to 10 gpm pilot system to evaluate water quality, denitrification achieved, and the impact on filtration. During Phase 2 of the study, a demonstration system capable of treating 300 gpm or more will be installed and operated. to develop detailed cost data on the process. Preliminary estimates suggest that biological denitrification compares quite favorably to both ion exchange and reverse osmosis, which are the two technologies used to remove nitrates today.

**Recommendations**

- Biological denitrification should be further pursued for nitrate removal and reactivation of contaminated shut-in wells. Commercial demonstration and public awareness should be the continuing focus of this technology. Biological denitrification is estimated to be equal to or less than conventional treatment options such as ion exchange and reverse osmosis. The broad range in costs for the conventional treatment technologies ($0.55 to $ 5.20 per thousand gallons treated) is the result of brine disposal costs and electricity costs, which vary depending on the location. In California, these disposal costs and power costs are expected to be on the high side of these ranges. Recent California's power shortage issues may limit the application of ion exchange and reverse osmosis from near-term commercial deployment.

## Benefits to California

Given the tremendous difficulties of removing nitrate from potable water supplies using conventional treatment processes, biological denitrification is a potentially attractive alternative. This innovative process can significantly reduce disposal concerns as well as permitting and infrastructure buildups. Reactivation of shut-in wells due to nitrate contamination can be a viable source of supply water both for local communities and new developments.

*Task 2.3 – Solids Removal Technologies*

MWD Study

**Objectives**

- Evaluate pilot-scale conventional treatment with and without ozone/ biofiltration, and microfiltration processes as the pretreatment step to RO desalting
- Evaluate full-scale conventional treatment as the pretreatment step to RO desalting
- Model the cost savings associated with a 100 mgd desalting plant using conventional treatment (both with and without ozone and biologically active filters) versus microfiltration as the pretreatment step

**Outcomes**

*Pilot-Scale Testing*

- Microfiltration produced water containing lower particle counts, turbidity, and silt density index (SDI) than either conventional treatment or conventional treatment with ozone/biofiltration.
- Pretreatment using conventional treatment showed the poorest RO performance in terms of maintaining stable flux over time, followed by conventional treatment with ozone/biofiltration, and finally microfiltration. Salt rejection of the membranes for all three pretreatment technologies ranged from 97 to 99 percent

*Full-Scale Testing*

With Aluminum Sulfate

- Five different RO membranes were tested using alum coagulation and chloramines. Results revealed rapid deterioration in specific flux as well as progressive reductions in salt rejection

With Ferric Chloride

- Instead of declining as in alum coagulation, the specific flux using ferric chloride and chloramines increased over time for all membranes. However, salt rejection for each membrane decreased significantly during testing.
- Preliminary cost estimates showed that existing conventional treatment plant was the lowest cost option ($0.39/1000 gal of finished water). MF showed 10 percent higher cost ($0.44/1000 gal) due to additional pretreatment facilities needed. The addition of ozone and biological filtration lowered the RO capital costs, but increased the overall treatment costs to $0.52/1000 gal, due to need for new pretreatment equipment.

**Conclusions**

## Pilot-Scale Results

- Microfiltration provided the highest quality and lowest cleaning frequency water to the RO process. Conventional treatment required chemical cleaning three times in three-month test period due to organic and biological fouling. Performance was improved with the addition of pre-ozonation and biologically-active filters.

## Full-scale Results

- Testing with full-scale conventional drinking water treatment showed differing results. Conventional treatment using both aluminum sulfate and ferric chloride coagulation showed adverse membrane performance which could hinder full-scale RO implementation. However, salt rejection was largely unaffected.
- The addition of either ozone and biological filtration or MF lowered the RO capital costs, but increased the overall treatment costs due to the need for new pretreatment equipment.

**Recommendations**

- Additional applied research is needed to optimize the conventional treatment process with and without ozone/biofiltration. A better understanding of the improved performance under the ozone/biofiltration pretreatment and its effects on the NOM of the water are needed. Additional work is also needed to better understand the full effects of interaction of different chemicals such as: coagulants (i.e. ferric, alum), disinfectants (i.e. chloramines), and antiscalants on the surface of the membrane.
- Microfiltration is the optimal pretreatment technology to provide the best feed-water for RO membranes with minimum fouling. However, additional work with conventional treatment processes may help water treatment plants use existing infrastructure as pretreatment to RO, thereby saving capital costs.

**Benefits to California**

Study results will enable local municipalities to adopt desalination technologies to treat current and previously unusable potable water supplies. Economic benefit is the reduction of societal damages to the public and private sectors due to high salinity of the Colorado River water (CRW). An additional benefit is the reduction of energy needed to reduce TDS of the CRW over currently available technologies. Technologies evaluated in this task may also be applicable to other source waters in California.

OCWD Study

**Objectives**

- Investigate microporous membrane module potting technique, membrane symmetry, fiber modulus of elasticity, fiber thickness, module flow pattern (inside-out or outside-in), and membrane material

- Develop mathematical modeling using structure-fluid interactions with analysis of membrane failure made to test performance at OCWD pilot- and demonstration-scale facilities

**Outcomes**

SEMs images were created for the five membrane fibers. Tensile testing results of the hollow fiber membranes were performed. A structural and a fluid model of a dynamically potted module with an elastomer overlay were developed using the symmetry, thickness, and strength data.

**Conclusions**

Correlations between membrane and module properties and membrane fiber failure (i.e., loss of integrity) were difficult to make because only two membrane fibers (the PM100s and PVDF fibers) underwent both materials testing and performance testing. Preliminary modeling results found the existence of additional stresses at the fiber/potting juncture which might possibly lead to the formation of fractures.

**Recommendations**

Future efforts should include evaluations of immersed hollow fiber membranes and the impact of backwashing (using both air and water) on hollow fiber membrane integrity. The current model for pressure-driven membranes could be modified to evaluate suction-driven membranes or to evaluate the effects of air and water backwashing. Similar to the current investigation, results from the modified structure-fluid model would be combined with analysis of membrane failure for OCWD membrane systems.

**Benefits to California**

Preventing microporous fiber breakage will have a significant effect on water treatment and wastewater reclamation in California and throughout the world. The performance of reverse osmosis membranes in indirect potable reuse and the efficacy of disinfection processes (chlorination and ultraviolet irradiation) in direct non-potable reuse are directly dependent on MF and UF fiber integrity.

*Task 2.4 – Salinity Removal Technologies*

MWD Study

**Objectives**

- Investigate the performance of experimental RO membranes and NF membranes
- Evaluate long-term fouling rate of RO membranes using conventionally pretreated water.
- Determine potential cost savings using experimental membrane flux and salt rejection data
- Evaluate various commercial and generic antiscalants to prevent scale formation during RO treatment of Colorado River water.

**Outcomes**

- Of the five RO membranes evaluated, RO1 (Dow Separation Processes, FilmTec Enhanced LE) provided the highest specific flux (0.37 gfd/psi) while still maintaining high salt rejection (98.8 percent). Performance data for NF membranes provided a wider range of variation in water production and salt rejection properties than RO membranes. NF membrane NF1 (Dow Separation Processes, FilmTec NF90) showed comparable specific flux and salt rejection to that of RO1.
- Ion hydrated radius and solution pH had a direct impact on the salt rejection behavior of NF membranes. Generally, as the hydrated radius increased (e.g., from sodium to sulfate), the rejection of that ion also increased. Additionally, operation at low pH conditions increased NF membrane salt rejection through chemically tightening of the membrane surface.
- All four experimental RO membranes have overall membrane system costs at least 15 percent lower than commercially available RO membranes. Two of the NF membranes tested demonstrated superior performance in specific flux and salt rejection over a current commercially available ultra-low-pressure RO membrane, resulting in 19 and 14 % cost savings, respectively.

**Conclusions**

- With the development of polyamide membranes, not only has the operating pressures for membrane systems decreased, but the water production per psi has also increased substantially.
- NF membranes operate at significantly higher flux rates than RO membranes, but exhibit poorer salt rejection.
- Closed-loop membrane testing, while inexpensive, may not provide representative water quality conditions and single-pass, multi-array membrane systems are not only expensive but have high water flow rate demands (up to 20 gpm).

**Recommendations**

- Further research is needed to wed the high water production of NF membranes with the high salt rejection of RO membranes. Next generation membranes that are either chlorine tolerant to prevent biofouling or exhibit unique surface charge characteristics to prevent particle and bacterial adhesion, or even scaling should also be developed.
- Smaller, single-pass membrane test systems need to be developed.
- A standardized protocol needs to be developed for interpreting RO membrane and water quality data to judge antiscalant effectiveness

**Benefits to California**

- Results from this study will enable local municipalities to adopt desalination technologies to treat currently and previously unusable potable water supplies.
- The primary economic benefit is the reduction of societal damages to the public and private sectors due to high salinity of Colorado River water. An additional

benefit is the reduction of energy usage to reduce the TDS of CRW over currently available technologies.

OCWD Study

**Objectives**

The objectives of this research were to study RO membranes' performance for salinity removal using different materials as well as feed sources. Part of research also examined treatment methods and options for the brine concentrate generated from the process. Specifically the objectives address: 1) studying and developing new RO membranes that are resistant to chlorine; 2) investigating nitrification and denitrification of RO brine (waste); and 3) testing the RO and MF processes on the wastewater treatment side.

**Outcomes**

**A. Chlorine Tolerant Membranes**

- Chlorine tolerant membrane performance was found to be equal, or superior to traditional commercial RO membranes
- Water quality was comparable while the total product water production was generally greater than the commercial membranes. The rate at which water production (or flux) declined was also lower than the commercial membranes.
- Commercial TFC membranes in the marketplace lack chemical tolerance to such oxidants as chlorine.

**B. Brine Disposal**

- The FBBR-GAC system has proven very efficient both in terms of process and energy consumption for the denitrification and sulfate reduction of brine concentrates. The optimum operating parameters were determined in this research.
- Preliminary laboratory-scale experiments revealed that the FBBR-GAC process is capable of removing approximately 45% of sulfate and 100% nitrate.

**C. IMANS™.**

- Initial testing of the IMANS™ process for wastewater treatment combined with water reclamation has shown promising results in sustainable performance and cost effectiveness.
- Potential capital cost and significant O&M cost savings are predicted for an IMANS™ approach compared with the conventional membrane approach for treatment of secondary wastewater effluent
- This established the technical feasibility of the IMANS™ process combination, even under challenging test conditions such as use of a six-year-old MF pilot

## Conclusions and Recommendations

### A. Chlorine Tolerant Membranes

**Conclusions**

- CPTC membrane was equal or superior to traditional commercial membranes for long-term performance
- CPTC membrane looks promising as a membrane that could successfully treat high fouling water sources without compromising membrane integrity and performance due to fouling and chemical degradation.

**Recommendations**

- The successful development and widespread implementation of a new polymer membrane is a timely process.
- More testing will be required to determine the practicability of this membrane as an alternative to conventional TFC membranes in treating high fouling water and wastewater sources.

**Benefits to California**

- The use of highly efficient, low fouling membranes would ultimately increase product water throughput while minimizing associated treatment costs.
- TFC polyamide membranes operate at lower operating pressures than cellulose acetate membranes, which can translate into significant energy savings of 30% to 40%. Using a lower pressure TFC membrane that exhibits fouling resistance would further reduce energy costs.
- Less biofilm proliferation and accumulation on the membrane surface would result in lower operating pressures and subsequently lower energy costs.

### B. Brine Disposal

**Conclusions**

- The optimum temperature range for the denitrification was determined to be between 20°C and 40°C.
- The total dissolved solid (TDS) concentration had insignificant effect on the denitrification rate.
- Preliminary laboratory-scale experiments revealed that the FBBR-GAC process is capable of removing approximately 45% of sulfate and 100% nitrate.

**Recommendations**

- The FBBR-GAC process needs to be further investigated in laboratory and pilot scales relative to energy efficiency and cost-effectiveness.
- More investigation is needed to upgrade the system for better sulfate removal.
- A model and detailed experimentations need to be developed for biological removal in dual-substrate systems (nitrate and sulfate).

**Benefits to California**

- Water recycling is foreseen as one of the best alternatives to meet the ever-increasing water demand in Southern California. It is through recycled water that the depleted groundwaters are replenished, saline water intrusion from the ocean is prevented, and surface water supplies are augmented.
- The Fluidized Bed Biofilm Reactor with Granular Activated Carbon technology has been proven to be very effective in the treatment of the RO brine concentrates. One notable advantage of fluidized bed reactors is that they require minimal space, and is relatively small as compared to conventional systems because of excessive biomass growth.
- The reaction time is short and the treatment efficiency is high, making it easily adoptable by the utilities planning to employ the RO technology to recycle water in residential areas where land availability is scarce or limited.

**C. IMANS™**

**Conclusions**

- The initial testing of the IMANS™ process approach for wastewater treatment combined with water reclamation has shown promising results in terms of sustainable performance and cost effectiveness.
- Potential capital cost savings and significant O&M cost savings are predicted for an IMANS™ approach compared with the conventional approach of using membranes to treat secondary wastewater effluent.
- Elimination of the secondary wastewater treatment step, lower life cycle costs, 50 percent less solids production, and smaller plant footprint, all establish the potential benefits of this new approach to wastewater treatment and reclamation using membrane filtration on primary wastewater effluent.

**Recommendations**

- Research is needed to study how other configurations of MF units could treat primary effluent.
- It is equally important to establish communication with the regulatory agencies to discuss possible alternatives for reuse and discharge prior to commercial development

**Benefits to California**

- This research and demonstration testing could significantly alter the manner in which wastewater agencies discharge waste effluent into the ocean or any other water body. By evaluating the microfiltration process as a means of disposing primary effluent, alternate methods can help better mange waste discharges.

*Task 2.5 – Investigate Disinfection Alternatives*

MWD Study

**Objectives**

- Evaluate ability of heterotrophic bacteria to repair or regrow following UV treatment
- Compare disinfection effectiveness of pulsed UV and medium-pressure UV lamps against single-stranded RNA virus MS-2
- Evaluate disinfection effectiveness of UV lamps against two organisms, phi-6 and Bacillus subtilis
- Determine ability of *Cryptosporidium parvum* to self-repair infectivity after exposure to UV light
- Determine disinfection effectiveness of UV light against Giardia lamblia, protozoan pathogen found in drinking water

**Outcomes**

- UV light at 20 mJ/cm$^2$ produces equivalent effect on heterotrophic bacteria as chlorine (1 minute contact) and chloramines (61 minutes contact). The three treatment techniques each provided more than 3.5 $\log_{10}$ inactivation of bacteria.
- UV was effective in disinfecting three organisms: *B. subtilis* aerobic spores, MS-2 coliphage, and phi-6 bacteriophage, with a dose of 40 mJ/cm$^2$ providing 1.9, 1.5, and 2.0 $\log_{10}$ inactivation, respectively.
- Study results found that a very low UV dose of 1.4 mJ/cm$^2$ would provide a 2 $\log_{10}$ inactivation of *G. lamblia*.
- Experiments were conducted to determine if a conventional medium-pressure UV lamp and a pulsed-UV lamp could effectively inactivate heterotrophic bacteria, *B. subtilis*, MS-2, phi-6, and *C. parvum*. Across all the experiments for disinfection, there appears to be no significant difference in the results obtained when using one lamp or the other.
- This study also evaluated the effects of UV only, compared with the effects of UV followed by addition of chloramines, on the biological stability of treated samples. Study results showed that regrowth occurs within a 3-day period with UV dose alone of up to 60 mJ/cm$^2$. However, when treated with 20 mJ/cm$^2$ UV dose followed by a chloramine dose of 2.6 mg/L, the samples remained biologically stable for at least 7 days.

**Conclusions**

- UV light was effective in the treatment of *C. parvum*, but it could not be determined The protozoa and heterotrophic bacteria were more susceptible to UV light, with dosages of less than 20 mJ/cm$^2$ providing 2 $\log_{10}$ inactivation. Organisms more resistant to UV light were the double-stranded RNA virus phi-6, followed by *B. subtilis* and then the single stranded RNA virus MS-2. For these organisms, a UV dose between 40 and 53 mJ/cm$^2$ was required to provide 2 $\log_{10}$ inactivation. The disinfection provided by UV on the human pathogen *G. lamblia* was even more effective than previously reported for *G. muris*, a more easily handled rodent parasite.

- This task study shows that the process of using UV light to control post-filtration heterotrophic bacteria would need to be followed by a residual disinfectant such as chlorine or chloramines to provide a water with biological stability.
- The disinfection provided by either a medium-pressure, continuous-wave UV lamp or an innovative pulsed-UV lamp was similar when compared, on an equivalent UV dose basis. Both lamps whether or not C. parvum could repair itself following UV treatment.

**Recommendations**

- Future studies should determine if *C. parvum* repair mechanisms may exist after UV treatment
- To better quantify effects of organism repair in future studies, it would be beneficial to wait until improvements in *C. parvum* infectivity assays are made to reduce variability
- Future research must complement the bench-scale data by evaluating the process efficiency and hydraulic characteristics of large-scale UV reactors.

**Benefits to California**

UV disinfection is fast becoming a great benefit to California water treatment utilities. However, recommendations stated above should be followed before implementing large-scale UV technology. Although the process shows to be viable at the bench-scale, large-scale application for on-line monitoring are still in development and should be evaluated before implementing the technology as a reliable barrier to waterborne human disease and illness.

**<u>OCWD Study (Task 2.5 Disinfection Alternatives)</u>**

**Objectives**

- Evaluate the low-pressure high-intensity open channel UV system to demonstrate compliance with the California Reclamation Criteria" and to meet Title 22 standards.
- Determine the efficiency of UV disinfection for inactivation of protozoa.
- Establish dose curve for pulsed UV and compare the performance of pulsed UV for disinfection of microorganisms using various water matrices.

**Project Outcomes**

- Evaluation of Wedeco-Ideal Horizons TAK 55 System
  The TAK 55 system was found to be most effective when used with three banks in series and when the flow rate was limited to 17 gpm / lamp. The system proved to be successful in meeting the criteria established by State of California Title 22 Wastewater Reclamation Criteria.
- Efficiency of UV for Protozoa Inactivation
  The use of collimated beam apparatus proved that UV is effective for inactivation of protozoa species including Giardia muris and Bacillus subtillus. It was found that the low pressure, high intensity collimated beam apparatus was most efficient but that all three systems were equally effective.

- Evaluation of Pulsed UV
  The pulsed UV system was originally designed to treat surface water sources, but was shown to be successful for the disinfection of treated wastewater. The addition of a baffle system to the pulsed UV eight inch diameter treatment vessel proved to be key to the system's effectiveness.

**Conclusions**

- Ultraviolet disinfection is an important technology for reclamation projects.
- Low-pressure, high-intensity open channel UV systems were effective for meeting California's Title 22 reclamation criteria.
- Ultraviolet technologies of varying types: pulsed, low pressure-high intensity, and medium pressure were effective for the inactivation of protozoa.
- Pulsed UV technology had comparable effectiveness to conventional UV for the disinfection of various microorganisms in various water matrices.

**Recommendations**

- Evaluation of Wedeco-Ideal Horizons TAK 55 System
  The testing of the Wedeco-Ideal Horizons TAK 55 lamp technology has proven that this technology is viable for meeting the disinfections standards set by the California Title 22 guidelines for wastewater reclamation. It is recommended that this system be considered for use in future or current municipal reclamation projects.
- Efficiency of UV for Protozoa Inactivation
  Tests need to be run using G. muris as an indicator organism for evaluation on a pilot scale UV system without having to lower the transmittance to an unreasonable level. It is also necessary to find a way to keep the G. muris from sticking to the plastic batch tank and the plastic PVC pipes which are connected at the influent and effluent ends of the pilot UV units.
- Evaluation of Pulsed UV
  The next step that should occur would be to test the pulsed UV 8" diameter pilot unit on membrane treated wastewater.

**Benefits to California**

- The testing could lead to certification of the Wedeco-Ideal Horizons TAK 55 technology by the California Department of Health Services for use in Title 22 reclamation applications. The certification of this technology should lead to an increase in options for agencies that are in need of disinfection technologies for reclamation projects.
- Completing this task has benefited California in that it shows that low levels of UV radiation are able to disinfect harmful protozoa. This allows other agencies to use UV technology in place of conventional disinfection technologies, which may be more expensive or may create unwanted disinfection byproducts
- The benefits to California are that there is now documented research and pilot demonstration to show that pulsed UV technology can be applicable to disinfection for reclamation applications.

*Task 2.6 Investigate Solids Processing Techniques*

**Objectives:**

- Evaluate the economics of using the BIOFREEZE™ unit for conditioning water treatment plant residuals
- Determine if biological wastewater residuals can obtain the same separation rate as inorganic water treatment plant residuals
- Evaluate the economics of using BIOFREEZE™ for conditioning wastewater residuals
- Evaluate freeze concentration of reverse osmosis brine to determine if separation of salts can be achieved

**Outcomes**

The purpose of this study was to evaluate the effects of freeze-thaw technology on water and wastewater residuals. All testing took place at OCWD in Fountain Valley, CA, on specific residuals of the following types:

- Alum Sludge from a water treatment plant
  Volume Reduction -- The F/T conditioning process reduce sludge volume by an average of 16 percent, with a range of 6 to 26 %.
  Supernatant Quality --The solids concentration of the supernatant, collected after gravity thickening for 2 hours, ranged from 650 to 930 mg/L which were higher than EPRI's previous reports ranging from 100 to 375 mg/L.
  Gravity-Thickened Solids Concentration.
  The solids content of the gravity-thickened sludge ranged from 11 to 12.5 percent which were similar to previous EPRI studies.
  Dewatering Using A Belt Filter Press
  The solids concentration of gravity thickened solids dewatered on a pilot-scale belt filter press, ranged from 22.3 to 26 percent which were also similar to those reported by EPRI.
- Ferric Chloride Sludge from MWD's water treatment plant
  Volume Reduction -- The F/T conditioning reduce residuals volume by 45 to 81 percent.
  Supernatant Quality -- The solids concentration of the supernatant, collected after gravity thickening, ranged from 930 to 1,070 mg/L.
  Gravity-Thickened Solids Concentration
  The solids concentration of the gravity-thickened sludge had a percent solids range of 10 to 16 percent.
  Dewatering Using Belt Press -- The solids concentration of sludge dewatered on a belt filter press ranged from 22 to 32 percent.
- Biological Sludge from OCWD's wastewater plant thickened activated sludge (TWAS)

The DAF-thickened TWAS had a solids concentration of approximately 8 percent. Unlike the inorganic sludges, the sludges subjected to F/T conditioning in this study were not reduced in volume.

- Brine from OCWD's wastewater plant's MF and RO treatment
  The freeze concentration (FC) pilot testing produced ice with TDS concentrations which ranged between 2757 and 5100 mg/L, and averaged approximately 3800 mg/L.
  Volume Reduction -- For the FC test runs, the influent brine volume was reduced between 24 and 89.6 percent.
  Power Requirements -- Power consumption for these test runs ranged between 3.3 and 15.1 kWh. Power consumption per ton of product frozen varied between 118.7 and 393.6 kWh per ton. For a commercial F/T system , the power consumption should range between 24 and 40 kWh/ton.

## Conclusions

- Mechanical F/T is extremely effective at reducing inorganic residual volumes, achieving up to a 94% reduction.
- Mechanical F/T of the wastewater biological residuals collected for this study did not produce the high level of separation achieved with the inorganic sludges.
- FC of RO brine did produce a concentrating effect, and reduce the volume of concentrated brine for disposal. Results of the testing did not appear to achieve low concentrations of TDS in the ice (average ice TDS, 3260 mg/L; expected ice TDS, 500 mg/L).
- Most of the power data collected during this study was inaccurate due to the BIOFREEZE™ unit not being insulated..
- The economic analysis of the freeze/thaw method appeared to be cost competitive with conventional treatment of water residuals.

**Recommendations:**

- Additional demonstration testing needs to be completed to verify the results of previous testing. The testing should concentrate on the thickening step to verify the assumptions used in this report.
- Capital costs are a significant obstacle for application of F/T. It is recommended that additional freezing systems be evaluated to determine if the capital costs can be reduced.
- For the biological sludges, the BIOFREEZE™ system appears to be able to provide substantial benefits to anaerobic digestion. Further testing needs to be completed to confirm that increased methane production can be achieved and to what extent dewaterability of the sludges can be expected.

## Benefits to California

The freeze-thaw process can be used to condition the biological residual before anaerobic digestion. The benefits to California from the use this technology include:

- Increased methane generation capacity
- Increased dewaterability of sludge
- Reduce the amount of salt to be disposed in landfills from microfiltration-membrane treated wastes
- Reduce the amount of salt from chemically treated wastes to be disposed by ocean discharge

*Task 2.7 Perform Energy and Process Assessment*

### Objectives

To conserve energy, reduce chemical use, and improve energy efficiency by using an integrated approach to energy and process assessment at four selected municipal water and wastewater treatment facilities.

### Outcomes

This task surveyed and summarized the findings at four water and wastewater treatment plants in California:

- San Francisco's Harry Tracy water treatment plant
- Metropolitan Water District's Jensen filtration plant
- Union Sanitary District's wastewater plant
- Vallejo Sanitation and Flood Control District's wastewater plant.

Energy consumption and cost for each plant were determined based on plant flow and energy billings and demand usage. Energy conservation measures (ECMs) were developed at each plant. For the water plants, the ECMs include three lighting retrofits to improve efficiency and control, an energy management system, load shedding three systems during peak hours, modifications to improve the equipment efficiency of three processes, and an HVAC change to reduce cooling. For the wastewater treatment plants, the ECMs include two lighting retrofits to reduce lighting and improve control, two energy management systems, operational changes to two processes, modifications to two non-potable water systems to reduce load, equipment modifications to improve efficiency, load shedding during peak hours, changes to a cogeneration system, and a change to a discharge permit to lower demand.

**Conclusions**

Eleven energy conservation measures (ECMs) at the water plants and twelve at the wastewater plants were identified through this task. These ECMs are estimated to save 8,533,854 kWh annually, which produces a cost savings of approximately $564,580. The ECMs are summarized below:

**Summary of ECMs**

| Type of ECM | Number | Energy Savings (kWh) | Annual Cost Savings | Potential Rebates | Estimated Capital Cost | Recommended |
|---|---|---|---|---|---|---|
| Lighting Retrofits | 5 | 51 kW<br>402,924 kWh | $27,180 | $39,826 | $74,000 | YES |
| Energy Management System | 3 | 420 - 480 kW<br>0 kWh/yr | $37,300 | | $65,000 | YES |
| Load Shifting | 4 | 501 kW<br>58,500 kWh/yr | $49,800 | 5,625 | $3,000 | YES |
| Equipment Modifications | 4 | 362 kW,<br>941,810 kWh/yr | $54,800 | $114,595 | $50,250 | YES |
| HVAC Changes | 1 | 0 kW,<br>72,000 kWh/yr | $3,700 | | $2,000 | YES |
| Operational Changes | 2 | 75 kW<br>803,000 kWh | $44,800 | $35,640 | $30,000 | YES |
| Modify NPW System | 2 | 19 kW<br>762,120 kWh | $42,000 | $91,090 | $42,000 | YES |
| Cogen Changes | 1 | 600 kW<br>4,600,000 kWh | $254,000 | $180,000 | $205,000 | YES |
| Permit Changes | 1 | 127 kW<br>893,500 kWh | $51,000 | $80,415 | $150,000 | YES |
| **Total of Recommended ECMs** | | | **$564,580** | **$547,191** | **$621,250** | |

**Recommendations**

It is recommended to implement the ECMs identified in this project and to conduct new studies at other facilities throughout the state to further reduce electrical demand and conserve our natural resources

**Benefits to California**

The State of California benefits by the significant energy savings, conservation of natural resources, reduction in pollution, minimized costs, and improved quality of treatment which thereby protects the environment.

*Task 2.8 – Scale-up Issues*

MWD Study

**Objectives**

- Evaluate preliminary scale-up issues by assessing operational and water quality needs that impact design criteria for construction of a large-scale UV systems
- Conduct biodosimetry challenges to characterize performance in terms of transferred UV dose (UV dose measured at the bench-scale)
- Monitor UV reactor over a period of testing to evaluate process performance
- Determine the element productivity, ion selectivity, fouling potential, and cleaning cycle of a 16-in. and an 8-in.-diameter RO elements
- Perform economic analysis of a full-scale RO plant utilizing 8-in. versus 16-in. diameter elements

**Outcomes**

- It is possible to increase the output of a MF module by increasing the surface area without increasing the module cleaning requirement.
- Adequate contact time during pre-chlorination is essential for the control of microbial fouling of the membrane surface.
- The overall process recovery of the full-scale Pall microfiltration system was found to be 90% at a flux of 24 gallons per square foot per day and a backwash interval of 15 minutes.
- The optimum cleaning procedure involved a caustic cleaning with a 2% sodium hydroxide solution and 5000 ppm chlorine followed by a acid cleaning using a 2% citric acid solution.
- The amount of energy required by the full-scale Pall microfiltration system is 400 kWh per million gallons of water treated.
- It is possible to operate a full scale system with some exposure to direct sunlight. Over the course of a year and a half, no deterioration was found on either the coated or the uncoated modules.

**Conclusions**

- To meet the requirement established by OCWD for a three-week interval between chemical cleanings, an ideal process recovery for the full-scale MF system of 90% was established. The process recovery for the Pall MF system is largely dependant on the interval setting between the air scour and reverse flush processes. The settings of 22- minute interval established as part of this testing could be applied to other wastewater reclamation installations.
- The cleaning procedure for the Pall MF system can be varied by the amount, re-circulation time and soak time of the chemical. It was important to establish an effective cleaning protocol to meet the required three week cleaning interval. The caustic portion of the cleaning was found to be more important than the acid portion, because majority of the fouling was found to be organic and not inorganic (mineral scale) fouling. This resulted in a nearly ten hour caustic solution re-circulation requirement as opposed to two hours of the acid re-circulation.

**Recommendations**

- Continued testing is needed at the established process settings to verify long term validity.
- Microfiltration membrane integrity needs to be observed over a long-term period and testing using established cleaning procedure from this research be continued. Also, the procedure established here could be easily adjusted for other installations where water quality may differ.
- The power requirements established during this testing should be further compared with those established elsewhere for MF processes as well as with other conventional treatment technologies such as chemical clarification or multi-media filtration.

**Benefits to California**

Benefits to California are the establishment of microfiltration technology as a viable alternative for large-scale wastewater reclamation. The use of MF technology will allow for greater reclamation to occur and reduce California's dependence on imported water sources. In most cases the land required for MF is several times smaller than that of current reclamation treatment processes. This testing has established a good estimate of the power requirements of MF technology for wastewater reclamation.

2.8 OCWD Scale-up Study

**Objectives**

The objective was to evaluate performance of a microfiltration system on a commercial scale with useful design information for municipal wastewater reclamation projects. Several investigations were initiated to address critical design issues:

- Is it possible to increase the output of a MF module by increasing the surface area without increasing the module cleaning requirements?
- How important is prechlorination in the control of microbial fouling on the membrane surface?
- What is the effective process recovery of MF system consisting of multiple modules (What volume of waste is produced per volume of water treated)?
- How often is it necessary to clean a MF system that consists of multiple modules and what is the most effective cleaning solution?
- What are the energy requirements for a system consisting of multiple membrane modules?
- Is it necessary to install the system in a building or can the materials used to construct a multiple MF system stand up to repeated exposure to sunlight, wind and rain?

**Outcomes**

*UV Disinfection*

- Biodosimetry challenges were conducted with MS-2 coliphage. Challenge results coupled with weekly monitoring of inactivation of heterotrophic bacteria showed that the UV reactor provided adequate disinfection of biofilter effluent. With 2 to 4 lamps on, bacteria were consistently reduced by more than 3 $\log_{10}$.
- Study evaluated correlation between sensor and calibrated radiometer readings. Results indicate a linear relationship between the two. However, this relationship needs to be further characterized over a wider range of water quality (e.g., turbidity from 0.1 to 10.0 NTU) to understand sensor reliability for both filtered and unfiltered water applications.
- Although this study showed successes in microbial challenges of the UV reactor, results will need to be verified at larger scales. Alternatives to biodosimetry need to be explored so that large California utilities may have other UV reactor dose-characterization options.

*Large-Scale Reveres Osmosis Desalination*

- A 16-in. diameter RO element was operated in parallel with a conventional 8-in. diameter element for over 2,500 hours. The specific flux of the 16-in. element (0.23 gfd/psi) was 20 percent lower than the average specific flux of the 8-in. element (0.28 gfd/psi). Both elements removed greater than 98 percent of the influent TDS. Differences in the performance were attributed to design issues associated with the 16-in. element.
- The large-diameter 16-in. elements are estimated to reduce RO plant capital costs by nearly 24 percent and overall costs (capital costs and O&M costs) by approximately 10 percent. Brine disposal costs were not included in the analysis. The use of large-diameter elements also reduced the overall plant footprint which resulted in a 24 percent savings for the building costs, as well as savings on system-wide controls and electrical equipment.

**Conclusions**

- This study developed a cursory correlation between sensor readings and calibrated radiometer readings which showed a linear relationship over the range studied.
- Although this study showed successes in microbial challenges of the UV reactor, larger-scale reactors will require validation. Alternatives to biodosimetry need to be explored so that large California utilities may have other UV reactor dose-characterization options.
- Large-diameter RO elements look very promising in reducing RO desalination costs for large-scale applications. Evaluation of one of the first 16-in. diameter prototype elements revealed that inefficiencies in the design currently exist. Membrane manufacturers are expected to improve the efficiency of the 16-in. element as research progresses.

**Recommendations**

Additional research is needed to study:

- The effects of water quality and water treatment chemicals on UV disinfection and alternatives to microbial biodosimetry in characterizing UV reactor dose. Characterization of sensor readings to a known standard (i.e., radiometry) should also be continued.
- A second-generation 16-in. diameter element is needed to eliminate the inefficiencies observed in the first prototype element. Improvements in membrane design and optimization of the pretreatment process will help improve membrane productivity and reduce fouling, which minimizes both capital and O&M costs. An important issue in the future is loading and unloading of membranes. A dry 16-in.-diameter element weighs approximately 200 lbs and when wetted, an individual element can weigh over 300 lbs.

**Benefits to California**

UV treatment of drinking water could be a great benefit to California by allowing a relatively low-cost technology to provide enhanced disinfection and protection of public health..The development of large, 16-in. diameter elements will benefit the entire state of California by lowering the cost of desalination and reducing the energy requirements to treat brackish water. The successful development of these large-diameter elements will help to significantly lower cost of new, large-scale desalination facilities (greater than 100 mgd) by taking better advantage of economies of scale.

*Task 2.8 Technology Transfer*

As research breakthroughs and other important results were achieved, EPRI and AWWARF provided an aggressive technology transfer effort including publishing technical information bulletins, organizing general information seminars, and conducting research needs assessment workshops to disseminate research findings to the municipal water community and related industries.

The information bulletins presented technical concepts in a reader-friendly format, incorporating graphics and easy-to-understand tables and charts. Because it is extremely important to emphasize communication between agencies and the general public, general information workshops were a major part of the technology transfer approach. The goal of the workshops was to present progress-to-date, exchange information, and obtain timely input. Three one-day workshops were held. The first workshop gathered input from industry experts, technology users, government agencies, and general participants to determine future workshop schedules and agendas. Workshop announcements, and a notification strategy, such as newspapers and trade journals, were proposed at the first workshop. Since research results often have a significant impact on the direction of future projects, the remaining two technical workshops were held to share technical information and provide feedback on research endeavors.

# Abstract

This study focused on the development of alternative water source and using electrotechnologies that could significantly reduce energy use and minimize environmental problems. Six innovative water/wastewater treatment process technologies were researched and evaluated at MWD and OCWD facilities. These include: advanced oxidation processes, biological denitrification, solids removal technologies, salinity removal technologies, disinfection alternatives, solid processing techniques. In addition, energy and process assessments were performed at two full scale water and two wastewater treatment facilities. To insure that these research technologies can be commercially deployed, an additional task was performed to address the scale-up issues and feedback from stakeholders through a series of three technology transfer workshops.

The following is a summary of conclusions derived from these tasks:

Task 1 assessed pulsed ultraviolet-radiation (UV), ozone, and PEROXONE as advanced oxidation processes. Study results showed that pulsed UV is effective in bromate and N-nitrosodimethylamine (NDMA) reduction, but is not effective for Methyl *t*-butyl ether (MTBE), perchlorate, and taste-and-odor compounds at normal dosages.

Task 2 evaluated biological denitrification process. Although pilot demonstration was cost effective, commercial application of the process for potable use was declined by the City of Modesto because of potential health risk concerns using bacteria.

Task 3 studied microfiltration as a pretreatment step for reverse osmosis (RO) desalting. Both pilot and full-scale demonstration results were superior to conventional chemical treatment.

Task 4 investigated nano-filtration (NF) membranes, low pressure RO, and chlorine tolerant membranes for salinity removal. All technologies showed varying degrees of success. Additional research is needed to wed high water production NF with the high salt rejection of RO system.

Task 5 evaluated UV disinfection for inactivation of virus, heterotrophic bacteria, and protozoa. Research showed that protozoa and heterotrophic bacteria are more susceptible to UV light than virus which would require post treatment with chlorine or chloramines to prevent re-growth.

Task 6 studied Freeze/thaw (F/T) as a solids-residual conditioning process. Results indicated that F/T is extremely effective in reducing inorganic residual volumes but not as successful in reducing biological sludge volumes.

Task 7 presented energy and process assessments (audits) at four municipal water/wastewater treatment facilities. Eleven energy conservation measures (ECMs) at two water treatment and twelve at wastewater treatment plants totaling a load reduction of 8,533,854 kWh annually.

Task 8 performed technology scale-up studies and conducted three technology transfer workshops. All demonstrations of large scale-up research units for UV disinfection, microfiltration and RO desalination showed promising results but need additional research to validate study conclusions. Technology transfer workshops and technology briefs were successfully deployed.

Major benefits of the study to California include: productivity improvement at treatment facilities, plant throughput increase, energy conservation, system cost reduction, waste and chemical use reduction, and job creation.

**Keywords:** advanced oxidation, biological denitrification, bacteria, bromate, energy and process assessment, energy conservation, energy conservation measures, freeze/thaw, microfiltration, MTBE, nanofiltration, NDMA, oxidation, ozone, perchlorate, peroxone, protozoa, technology transfer workshops, UV disinfection, virus.

## 1.0 Introduction

### 1.1. Background and Overview

The sixteen million residents of Southern California and a dynamic $450 billion regional economy depend on a reliable and affordable supply of potable water. By the year 2020, however, existing water supplies will only meet the needs of four out of five families. It is vitally important for Southern California to develop alternate supplies in an environmentally sound manner. Most of the current supply is imported from Northern California or the Colorado River. The transfer of water requires at least 10 million barrels of oil per year to generate the power required by the vast pumping system.

Southern California contains sufficient supplies of contaminated groundwater, municipal wastewater, and agricultural drainage to meet future demand (collectively termed "non-traditional" supplies). Agricultural drainage and reclaimed water supplies are estimated at 1.0 and 1.1 million acre-feet (maf), respectively. High concentrations of dissolved salts (salinity) prevent the development of these sources as alternative potable supplies. Agricultural drainage and municipal wastewater contain between 2000 to 3000 milligrams per liter (mg/L) and 900 to 1200 mg/L of total dissolved solids (TDS), respectively. Approximately 16.0 maf of groundwater in Southern California is either brackish (2000 - 15,000 mg/L TDS), contaminated by nitrates introduced by agricultural use, or contaminated with organics, such as gasoline by-products from nearby industries. Alone this water is enough to supply the state's entire 32 million people with water for four years. Unfortunately, the conventional approach to water treatment does not include a process for salt removal, while the traditional desalting technologies, such as thermal distillation, are more effective on seawater (33,000 mg/l TDS) than lower TDS sources. Desalting seawater is not a solution, as the treatment costs are four to five times higher than the current cost of treating groundwater and surface waters. Fortunately, non-thermal (electrotechnologies) desalting processes, such as reverse osmosis (RO), are more effective on lower TDS waters at a cost that is comparable to conventional processes.

### 1.2. Project Approach

This study focused on electrotechnologies that could significantly reduce energy use while simultaneously minimizing environmental problems. Six innovative water/wastewater treatment process technologies were evaluated by a consortium consisting of the Metropolitan Water District of Southern California (Metropolitan), the Orange County Water District (OCWD), and the Electric Power Research Institute (EPRI) under the project management of Southern California Edison (SCE). These agencies were assisted by expertise from the University of California at Riverside, Lawrence Livermore National Laboratory, the American Water Works Association Research Foundation (AWWARF), and a blue ribbon panel of the regions leading water and wastewater consultants. The electrotechnologies were chosen specifically for their potential to mitigate existing environmental problems associated with water/wastewater treatment and their ability to remove salts to improve water quality and develop new sources of water. More importantly, some of these technologies had been developed to the stage where critical evaluations of process efficiency and scale-up issues were needed to insure successful deployment. To this end, eight specific tasks were formulated to achieve the study objectives. These include:

- Investigate advanced oxidation processes,

- Investigate biological denitrification,
- Investigate solids removal technologies,
- Investigate salinity removal technologies,
- Investigate disinfection alternatives
- Investigate solid processing techniques,
- Perform energy and process assessment, and
- Conduct technology transfer and process scale-up for commercial deployment.

### 1.3. Report Organization

Section 2.0, Individual Task Discussion is organized by task with objectives, approach, outcomes, conclusions and recommendations, and benefits to California provided under each of the eight tasks. Section 3.0, Project Summary Conclusions; Section 4.0, Project Summary Recommendations; Section 5.0, Project Summary Benefits to California; and Section 6, References are also organized by task. Section 7.0 provides a glossary of terms used in this report.

In addition there are eighteen appendices that are again organized by task.

| | |
|---|---|
| Appendix I: | Task 2.1: Report by MWD on Advanced Oxidation Processes |
| Appendix II: | Task 2.2: Report by EPRI on Biological Denitrification |
| Appendix IIIa: | Task 2.3 A: Report by MWD on Solids Removal Technologies |
| Appendix IIIb: | Task 2.3 B: Report by Univ. of Nevada, Reno on Preventing Membrane Fiber Breakage |
| Appendix IVa: | Task 2.4 A: Report by MWD on Salinity Removal Technologies |
| Appendix IVb1: | Task 2.4 B1: Report by OCWD on Salinity Removal Technologies |
| Appendix IVcb2: | Task 2.4 B2: Report by Univ. of So. Calif.(USC) on Denitrification of Brine |
| Appendix IVb3: | Task 2.4 B3: Report by Carollo Engineers, USC and OCWD on Salinity Removal Tech. |
| Appendix Va: | Task 2.5 A: Report by MWD on Disinfection Alternatives |
| Appendix Vb: | Task 2.5 B: Report by OCWD on Disinfection Alternatives |
| Appendix VI: | Task 2.6 Report by EPRI on Solids Processing Technologies |
| Appendix VII: | Task 2.7 Report by EPRI on Water & Wastewater Treatment Plant Energy Optimization |
| Appendix VIIa: | Task 2.7 A: Report by HDR on Vallejo Sanitation and Flood Control District Energy Audit |
| Appendix VIIb: | Task 2.7 B: Report by EPRI on Harry Tracy WTP and Baden Pumping Station Energy Audit |

Appendix VIIc: Task 2.7 C: Report by EPRI on Union Sanitation Dist. Wastewater Treatment Energy Audit

Appendix VIIIa: Task 2.8 A: Report by MWD on Scale-up Issues for UV Disinfection and RO Desalination

Appendix VIIIb: Task 2.8 B: Report by OCWD on Scale-p Issues for a Microfiltration System

Appendix VIIIc: Task 2.8 C: Report by EPRI on Technology Transfer

## 2.0 Individual Task Discussions

The following is a summary discussion of these eight tasks relative to objectives, outcomes, conclusions, recommendations and benefits to California.

### 2.1. Task 2.1 - Investigate Advanced Oxidation Processes

#### 2.1.1. Task Objectives:

- Study bromate reduction by Pulsed UV
- Evaluate MTBE reduction by Pulsed UV and ozone/peroxide
- Investigate NDMA treatment by Pulsed UV and ozone/peroxide
- Perform perchlorate reduction by Pulsed UV
- Assess taste and odor reduction by Pulsed UV

#### 2.1.2. Task approach

Consistent with the above objectives, six specific areas have been identified. The following is a discussion of the approach undertaken in each activity.

*Bromate Reduction by Pulsed-UV Light*

Bromate levels were varied to replicate three concentrations: 1) the amount of bromate that could possibly be formed if SPW or CRW, depending on which is available, was ozonated at normal levels to meet Surface Water Treatment Rule (SWTR) regulations (i.e., 1-$log_{10}$ *Giardia* inactivation and 3-$log_{10}$ virus inactivation) without pH control; 2) the amount of bromate that could possibly be formed if the natural water was ozonated at levels to meet future enhanced SWTR (ESWTR) regulations for disinfection (i.e., 1-$log_{10}$ *Cryptosporidium* inactivation which equals approximately 10-$log_{10}$ *Giardia* inactivation) without pH control; and, 3) a level above the preceding concentrations, as a worst case scenario. These targeted levels were 0.010 mg/L, 0.050 mg/L, and 0.100 mg/L, respectively.

Experiments were carried out in laboratory and natural waters. The difference between these cases were targeted to identify possible negative effects that natural water matrices (i.e., organic material and suspended particles) may have on the UV photolysis of bromate. The applied UV dose was carefully measured to increase the understanding of bromate destruction by UV. Dose measurement was conducted with a biological actinometer. Experiments were also conducted with addition of $H_2O_2$ to process water prior to UV treatment to form a significant concentration of hydroxyl radicals.

*MTBE Reduction by Pulsed-UV Light*

Pulsed-UV and pulsed-UV/$H_2O_2$ tests were conducted in two phases with laboratory water and a Southern California groundwater. Phase I was conducted in a completely mixed batch reactor (CMBR) to determine UV and $H_2O_2$ dosages for MTBE reduction. Two MTBE concentrations were evaluated (200 and 2,000 μg/L). Phase II was conducted in a continuously stirred tank reactor (CSTR) to validate CMBR testing and investigate impacts of other compounds (such as TBA) on MTBE destruction.

Reduction By Ozone and PEROXONE

Ozone/PEROXONE tests were conducted in two phases using a Southern California groundwater. Tests were performed in the CMBR to determine required ozone and $H_2O_2$ dosages. Effects of influent MTBE concentrations on MTBE removal were also tested with MTBE spikes of 200 and 2,000 µg/L. Procedures for experiments were as follows: 1) the test water was collected and spiked with MTBE (and other compounds if required); 2) water was pumped to the ozone treatment chamber; 3) initial water samples were taken from the test water; 4) ozone and $H_2O_2$ were continuously added; and, 5) treated water samples were collected at different time intervals.

*NDMA Reduction by Pulsed-UV Light*

Pulsed UV and pulsed UV/$H_2O_2$ tests for NDMA reduction were conducted in two different phases. Laboratory water, Colorado River water (CRW), and a Southern California groundwater with varied levels of NDMA were treated. Phase I was performed in the CMBR to determine the required UV dosages and $H_2O_2$. The effects of $NO_3^-$ and of influent NDMA concentrations on NDMA removal were also examined with 38 mg/L $NO_3^-$ spike and 0.1 and 3 µg/L NDMA spikes. Phase II was conducted in a CSTR to confirm the effects of other compounds on NDMA destruction and investigate possible reformation of NDMA. Procedures were similar to that used for MTBE treatment.

Reduction by Ozone and PEROXONE

Ozone and PEROXONE tests were conducted in two different phases using a Southern California groundwater. Phase I was performed in a CMBR to determine the required ozone and the $H_2O_2$ dosage. Effects of influent NDMA concentration were tested with 0.1 and 3 µg/ NDMA spikes respectively. Phase II was conducted in a CSTR to investigate the effects of applied ozone dose and validate optimized conditions.

Procedures were as follows: 1) test water was collected and spiked with NDMA and other compounds (if required); 2) water was pumped to the bench scale ozone treatment chamber and the reactor mixer was turned on; 3) initial samples were taken; 4) ozone and $H_2O_2$ were continuously added to the process water; and, 6) ozonated water samples were collected.

*Perchlorate Reduction by Pulsed-UV Light*

Pulsed UV tests with and without catalyst were conducted. Tests were performed in the CMBR to determine the required UV dose, develop perchlorate decay information, and investigate the evolution of perchlorate byproduct formation. Perchlorate reduction by ozone/PEROXONE was not evaluated because perchlorate is already the most highly oxidized state of chlorite possible.

*Taste-and-Odor Reduction by Pulsed-UV Light*

This subtask spiked known amounts of 2-methylisoborneol (MIB) and geosmin into CRW. Target baseline levels for each compound were 50 nanograms/L (ng/L), an amount found in MWD's raw water reservoirs. UV dose and $H_2O_2$ dose were varied to determine the most cost efficient operation of the system.

Experiments were conducted in the following matrix:

- Effects of increasing UV-alone dose (no $H_2O_2$)
- Effects of increasing $H_2O_2$ dose (UV dose remaining constant
- Effects of increasing UV dose ($H_2O_2$ dose remaining constant)
- Procedures for experiments were similar to the bromate experiments

*Methods and Materials*

**Aldehydes**

Formaldehyde and acetaldehyde were analyzed by a derivatization-extraction GC electron-capture detection method. Other aldehydes, such as glyoxal and methyl glyoxal, were analyzed by a modification (heated derivatization) of this method.

**Bromate**

Bromate tests were conducted by dissolving potassium bromate into the subject waters to target concentrations of 100, 50, and 10 µg/L. Bromate analyses were performed by a modified ion-chromatographic (IC) method.

**Bromide**

Bromide analyses were conducted on an ion chromatograph with a 20- or 50-µL sample loop. An ion-chromatography (IC) analytical column, an anion micromembrane suppresser, and a conductivity detector were used.

**Hydrogen Peroxide**

Two different methods were used for detection of residual $H_2O_2$. A fluorescence method was used when residuals were less than 1 mg/L and an iodometric titration method was used for more concentrated residuals.

**MTBE and MTBE Byproducts**

The method used a direct aqueous injection analytical technique for the routine analysis of MTBE and its likely degradation products. This injection technique, when coupled with detection by mass spectrometry allows simultaneous qualification and quantification of MTBE and all of its expected degradation products with a detection limit of 0.1, 0.1, 5.0, and 10 µg/L for MTBE, TBA, TBF, and acetone, respectively.

**NDMA**

Prior to June 1999, NDMA samples were analyzed by DataChem Labs, Inc. which extracted NDMA samples in a continuous liquid-liquid extractor and analyzed the extract by gas chromatography/mass spectrometry (GC/MS), with a selected ion-monitoring mode to determine NDMA with a detection limit of 0.020 µg/L. The Canadian Ministry of the Environment (Etobicoke, Ontario, Canada) analyzed NDMA samples taken after June 1999. NDMA was analyzed by a solid-phase extraction method combined with low-resolution GC/MS with a detection limit of 0.001 µg/L.

**Ozone Contactor Tests**

MTBE treatment by ozone was conducted with a pilot-scale ozone contactor, approximately 200-gal, consisting of an ozone contactor column, an ozone reactor column, a water recirculation pump, and a equalization tank. For each test, MTBE in a predetermined amount was mixed in an equilibrium tank. Water was pumped to the top of the ozone contactor from a 200-gal Nalgene® tank at 2.4 gpm. In the first contactor column, ozone gas was applied countercurrent to the treated water flow. The second contactor column served as a reactor chamber (no gas applied). Each ozone column was operated at a residence time of 10 min. Water levels were maintained at 16 ft in the 6-in diameter columns. Ozone was bubbled through 4-in diameter ceramic diffusers to generate fine bubbles. Ozone transfer efficiencies were above 98 percent in all tests. The capacity of the ozone generator was 1 lb/day, with oxygen or compressed air as the feed gas.

For NDMA tests, a bench-scale reactor was used, consisted of a gas tight, 20-L glass shell, with inlet and outlet ports for applying ozone gas and diverting the off gas to the ozone destruction unit. Ozone was bubbled directly to a mixing blade to increase the transfer efficiency of ozone. The liquid volume was 16 L, and the $H_2O_2$ was injected to the water by a peristaltic pump. A pump, with stainless steel tubing, was attached to the reactor bottom for sampling purposes during batch experiments. The same ozone generator was used as described above.

For NDMA flow-through tests, the batch setup was modified with two high-speed pumps attached to the reactor. The influent water line was extended to the bottom of the reactor, and the stainless steel tubing was placed at the surface of the water for the effluent line. $H_2O_2$ was applied by a peristaltic pump to the system. Samples were taken from the influent and the effluent lines.

**Perchlorate**

Perchlorate samples were analyzed by an ion chromatograph modified with a 200 μL-sample loop. An ion chromatography analytical column, an anion micromembrane suppressor, and a conductivity detector with a detection limit of 1.4 μg/L and reporting limit of 4.0 μg/L were used.

**Pulsed-UV Apparatus**

Pulsed-UV experiments were conducted using a 316 stainless steel bench-scale, completely mixed batch reactor (CMBR), containing a pulsed-UV lamp and a variable-speed mixer. The CMBR housed a 15-cm, xenon-filled, tungsten-electrode flash lamp which emitted polychromatic light across the UV, infrared, and visible spectra and was powered by a 5-kilowatt (kW) source that allowed pulse rates up to 30 Hz. Between pulses, a standby "simmer" mode consisting of a steady-state partial ionization of the xenon gas was maintained with a low current arc between the electrodes. Experiments were conducted with the lamp pulsing at 2, 10, or 25 Hz.

**Residual Ozone**

For residual ozone, method 4500-$O_3$ (APHA 1998) was slightly modified. The measurement was corrected for the absorbance of background organics at 800 nm.

**Simulated Distribution System Tests**

Water samples were dosed with chlorine at 1.5 mg/L and incubated at 25°C for 1 day. The chlorine dosage of 1.5 mg/L was used because chlorine demand tests indicated that this dosage was needed to maintain a residual of at least 0.2 mg/L after 24 h. Analyses were conducted on SDS samples to evaluate the formation of pentane-extractable disinfection by-products—such as total THMs, haloaceto-nitriles (HANs), haloketones (HKs), and chloropicrin—that employed modified THM liquid-liquid extraction.

**Miscellaneous**

Grab samples were collected for alkalinity, total organic carbon (TOC), conductivity, UV light absorbance, and nitrate analyses, which were all analyzed in accordance with Standard Methods (APHA 1998) procedures. Grab samples for turbidity were quantified turbidimeter and pH was measured by a pH meter calibrated daily with pH 7.0 and 10.0 buffer solutions.

**Taste-and-Odor Compounds**

MIB and geosmin were dissolved in water and analyzed using salted closed-loop stripping analysis (CLSA) followed by GC/MS identification. During CLSA, VOCs were stripped from the water by a recirculating air stream and adsorbed onto an activated carbon filter. The compounds were eluted from the filter with carbon disulfide. The obtained extract was then injected onto a GC/MS for identification and quantification by selective ion monitoring. The method detection level (MDL) was 2 ng/L for both geosmin and MIB.

### 2.1.3. Task Outcomes:

- Study bromate reduction by Pulsed UV – tests were conducted with up to 100 µg/L of bromate. Data were collected from both Collimated Beam (CB) screening tests and continuously stirred tank reactor (CSTR) tests. The CB tests demonstrated 6 percent bromate reduction after applying a UV dose of 110 mJ/cm$^2$. Subsequent laboratory water tests in the CSTR, with a starting bromate concentration of 50 µg/L or more, showed up to 89 percent bromate reduction after an applied dose of about 3,100 mJ/cm$^2$. With a starting concentration of 10 µg/L, bromate was reduced below detectable limits. In general, it was not feasible to achieve significant reduction in bromate at UV doses less than 100 mJ/cm$^2$. When compared to the UV dose required to achieve 1-log $_{10}$ inactivation of Cryptosporidium, it takes almost 1000 fold greater UV dose for the same reduction of bromate.
- Evaluate MTBE reduction by Pulsed UV and ozone/peroxide – Pulsed UV tests were investigated under 2 pulse rates (10 and 25 Hz) and two $H_2O_2$: MTBE molar rations (99.5 and 135). Figure 1 presents a summary of MTBE treatment plotted against this unit of UV dose measure. These data indicate the amount of UV energy required to reduce MTBE, with and without $H_2O_2$. Test data showed that without $H_2O_2$, a UV dose of 47,000 mJ/cm$^2$ reduced MTBE by 87 percent and adding 69 mg/L $H_2O_2$ lowered the required dose to 1600 mJ/cm$^2$. These UV and $H_2O_2$ doses, however, are prohibitive in drinking water applications. Ozone/peroxide (PEROXONE) tests were evaluated at two MTBE concentrations (2000 and 200 µg/L).

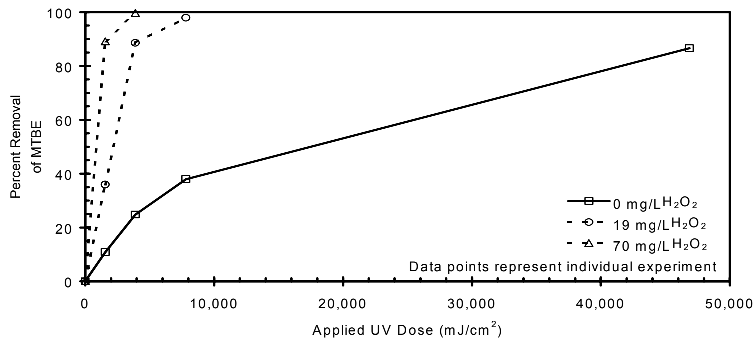



**Figure 1: Effect of UV and UV/$H_2O_2$ on MTBE**

- Figure 2 and Figure 3 show the effects of ozone dose, PEROXONE dose (at a constant $H_2O_2$ to ozone ratio of 1.0) and initial MTBE concentration on MTBE removal. At the higher MTBE concentration, PEROXONE removed substantially more MBTE than ozone alone. However, at the lower MBTE concentration, ozone and PEROXONE performed similarly.

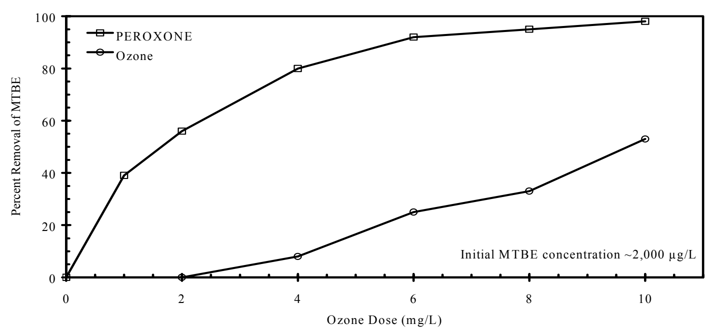



**Figure 2: Effect of Ozone and PEROXONE on MTBE Removal (Initial MTBE concentration = 2,000 µg/L)**

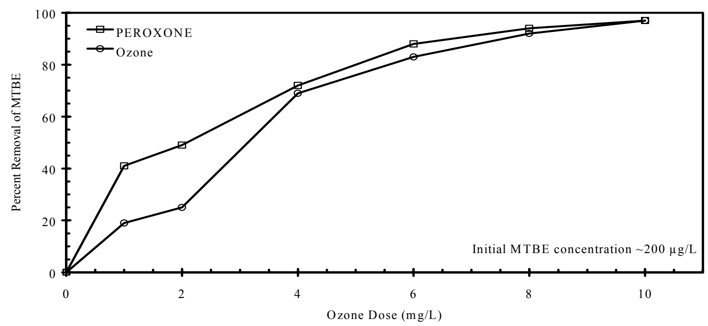



**Figure 3: Effect of Ozone and PEROXONE on MTBE Removal (initial MTBE concentration = 200 µg/L)**

- Investigate NDMA treatment by Pulsed UV and ozone/peroxide – test results showed that the addition of $H_2O_2$ did not improve NDMA removal in any of the test waters. However, water quality differences such as nitrate and turbidity could affect NDMA removal. Figure 4 shows the effect of nitrate has on NDMA removal in laboratory water. This data indicates that nitrate, which is present in many waters contaminated with NDMA, may reduce the efficiency of UV treatment. Reduction of NDMA by ozone (at 5 mg/L) was minimal but was much greater (50%) with PEROXONE at the same concentration.

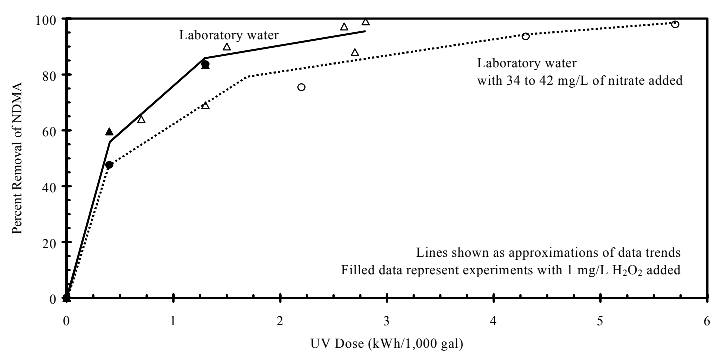



**Figure 4: Effect of Nitrate on UV Treatment of NDMA**

- Perform perchlorate reduction by Pulsed UV – tests were performed at a pulsed rate of 25 Hz. No measurable perchlorate reduction was observed because perchlorate does not absorb UV light even when pH of water was reduced.
- Assess taste and odor reduction by Pulsed UV – tests were performed using MIB and geosmin, by-products of algae and bacteria, as taste and odor indicator. As with MTBE results, very high doses of UV alone are required for MIB and geosmin reduction. Without $H_2O_2$, 10,100 mJ/cm$^2$ applied UV dose was needed

to reduce MIB and geosmin by 92 and 97 percent respectively. Adding 5.5 mg/L of $H_2O_2$, only 1,100 mJ/cm$^2$ was needed to achieve comparable results.

### 2.1.4. Conclusions and Recommendations

#### 2.1.4.1. Conclusions:

1) Bromate reduction by Pulsed UV

- Bromate reduction was more efficient in laboratory waters than natural waters, and the difference in treatment could not be explained fully by the change in water qualities. Specifically, results showed 3,100 mJ/cm$^2$ was needed to reduce bromate by 89 percent in laboratory water. In natural waters, at dosages up to 4,000 mJ/cm$^2$, only 18 percent bromate reduction was seen. The addition of $H_2O_2$ did not improve performance.

2a) MTBE reduction by Pulsed UV

- UV alone cannot effectively reduce MTBE;
- UV/$H_2O_2$ is effective in reducing MTBE;
- $H_2O_2$ dose strongly affects reduction efficiency of MTBE;
- MTBE byproducts reduced the effectiveness of pulsed UV/$H_2O_2$ treatment for MTBE
- A UV dose of 47,000 mJ/cm$^2$ was needed to reduce MTBE by 90 percent
- A UV dose of 1,600 mJ/cm$^2$ combined with 69 mg/L $H_2O_2$ reduced MTBE by 90 percent.

2b) MTBE reduction by Ozone and PEROXONE

- PEROXONE was more effective in oxidizing MTBE than ozone, particularly when water contained higher MTBE concentrations
- Ozone doses of 19 mg/L (with 47 mg/L $H_2O_2$) and 24 mg/L (with 30 mg/L $H_2O_2$) were needed to meet the secondary standard of 5 µg/L for 200 and 2,000 µg/L of MTBE, respectively
- MTBE by-products such as TBF, TBA, acetone, and aldehydes were identified and may have hindered MTBE removal efficiency
- TBF was produced immediately, followed by TBA, acetone, and formaldehyde
- Treatment of groundwater by ozone and PEROXONE produced bromate
- The addition of $H_2O_2$ prior to ozonation produced lower levels (< 13 µg/L) of bromate than ozone.

3a) NDMA Reduction by Pulsed UV

- UV alone is effective in removing NDMA
- Characteristics of water type played an important role for NDMA reduction due to the differences in transmittance and background constituents
- A strong competition for UV light absorption between NDMA and background organics (e.g., TOC and $UV_{254}$-absorbing organics) affected NDMA removal

- Nitrate competed with NDMA for absorbing UV light and consequently limited UV effectiveness
- Treatment is independent of initial NDMA concentration (at very low levels tested)
- A UV dose of 580 $mJ/cm^2$ reduced NDMA in groundwater by 90 percent
- A UV dose of 100 $mJ/cm^2$ reduced NDMA in groundwater by 51 percent.

3b) NDMA reduction by Ozone and PEROXONE

- Ozone alone is ineffective in NDMA reduction in drinking water
- PEROXONE improved NDMA removal efficiency compared to ozone alone
- NDMA (< 3ppb) destruction by PEROXONE depended on ozone dosage, but not on the initial NDMA concentrations

4) Perchlorate reduction by Pulsed UV

- Perchlorate was not reduced by UV
- Perchlorate concentration, $H_2O_2$ dose and pH had no effect on perchlorate reduction
- Elemental iron, an attempted catalyst for perchlorate reduction, had no effect, possibly because of interferences from dissolved oxygen
- pH had no effect on perchlorate reduction by UV in the presence of catalyst

5) Taste-and-Odor Compounds

- A UV dose of 10,100 $mJ/cm^2$ reduced MIB and geosmin by 92 and 97 percent respectively
- 100 $mJ/cm^2$ (a disinfection-level UV dose) and 5 mg/L $H_2O_2$ provided 86 and 96 percent reduction of MIB and geosmin, respectively.

#### 2.1.4.2. Commercialization Potential:

Ozone treatment requires much less energy when compared to UV for treatment of MTBE, NDMA, and T&O compounds. To reduce NDMA, MTBE, and T&O compounds (with $H_2O_2$), UV required approximately 1.5-fold, 20-fold, and 25-fold more energy than ozone, respectively. For ozone, reduction of T&O compounds required the least amount of energy with MTBE and NDMA requiring 2.5-fold and 6.5-fold more energy, respectively. For UV treatment, NDMA required the least amount of energy with T&O compounds, MTBE, and bromate requiring 2.5-fold, 5-fold, and 10-fold more energy, respectively. Energy requirement was nearly twice that required by ozone. Based on these results, ozone (already commercially feasible for treatment of T&O compounds) may be commercially feasible for MTBE treatment, but the increased costs to treat NDMA may be prohibitive. Although UV costs seem excessive, it still may be feasible to use it on a water quality basis, because it does not form as many DBPs as ozone.

#### 2.1.4.3. Recommendations:

Based on water quality issues and cost requirements, one of the technologies evaluated here could be applied for reduction of water contaminants. Although ozone may be significantly less energy-intensive when compared to UV for several of the micropollutants studied, UV may be a more appropriate option based on DBP formation potential. In considering these technologies, utilities must weigh energy and DBP costs prior to implementation.

#### 2.1.4.4. Benefits to California:

It is beneficial for California utilities to understand the limitations of advanced treatment techniques before implementation. As UV radiation may provide excellent disinfection efficiency and low DBP formation at disinfection-level dosages, the high energy requirements for treatment of micropollutants may cause utilities to consider ozone. Utilities must, however, also consider the level of DBPs that high ozone dosages may produce.

## 2.2. Task 2.2 – Biological Denitrifications

### 2.2.1. Task Objectives

*Objectives*

The project has four objectives:

- Demonstrate the *BioDen™* biological denitrification system is technically and economically viable at scale-up.
- Obtain California DHS approval for the *BioDen™* system as a viable treatment system for the removal of nitrate and the production of potable water.
- Demonstrate the effectiveness of ceramic filtration as a viable post treatment filtration technique. .
- Determine operational and maintenance costs for the *BioDen™* biological denitrification unit using the Pall Corp. ARIA℠ PVDF hollow fiber microfilter, specifically focusing on power consumption and methods to minimize power requirements during the Phase II demonstration.

### 2.2.2. Task Approach

The demonstration project will be separated into three phases: Phase 1 will be a 10-gpm pilot test for two months, Phase II will be a 300 gpm large scale demonstration evaluate for three months, followed by Phase III that will include an additional 300 gpm treatment capacity to complete the installation as a commercial plant. Final design details, operational procedures and overall treatment ability of the system will be determined during Phase I.

*Biological Denitrification – Overview*

Denitrification is the biological (bacterial) conversion of nitrate to harmless nitrogen gas. Biological denitrification is an aerobic respiration process where nitrate acts as the terminal electron acceptor while an external carbon source is the electron donor.

*Bacteria*

Several genera of bacteria can denitrify including *Achromobacter, Aerobacter, Alcaligenes, Bacillus, Brevibacterium, Falvobacterium, Lactobacillus, Micrococcus, Proteus, Psuedomonas*, and *Spirillum.* This large diversity and number of bacteria that can denitrify is due to the fact that the enzymatic pathway for nitrate reduction can be achieved by modifications within the bacterial cell. The large number of bacteria that can denitrify also means that denitrification is a relatively stable process and is possible in a wide range of environmental conditions.

As stated previously, biological denitrification by bacteria requires an external carbon source for energy. As stated in previously, by definition biological denitrification is carried out by heterotrophic (chemoorganotrophic) bacteria. In denitrification, dissimilatory nitrate reduction occurs in the following steps:

$$NO_3 \Rightarrow NO_2 \Rightarrow NO \Rightarrow N_2O \Rightarrow N_2$$

This multi-step reduction is a direct result of the cytochromes within the electron transport chains (ETC) inside the bacterial cell, although the biochemistry of these reactions is not well understood.

*Stoichiometry*

The stoichiometry of biological denitrification is dependent on the type of external carbon (supplemental) source used. Various reduced-carbon sources have been used including high fructose corn syrup (HFCS), ethanol, methanol, acetic acid, and denatured alcohol. Stoichiometric equations can be developed by both theoretical and laboratory investigations. Once the stoichiometric equation is known, then the amount of carbon required to destroy the nitrate ion can be determined.

*Operational and Environmental Variables*

Operational and environmental variables that affect denitrification include:

- Nitrate concentration
- Nitrite concentration
- Dissolved oxygen
- Temperature
- pH
- Ionic strength

In addition to those variable listed above that can affect denitrification performance, two micronutrients in particular are very important to denitrification performance. Those micronutrients are Vanadium and Molybdenum. These micronutrients are used in the production of cytochromes and enzymes specific for denitrification within the cell.

*BioDen™ Process*

The *BioDen™* process uses bacteria in conjunction with acetic acid (vinegar) to remove nitrates from water. This is an anaerobic biological process in which nitrates ($NO_3^-$) are converted by bacteria into harmless nitrogen gas ($N_2$) and carbon dioxide ($CO_2$). The bacteria that are used in the *BioDen™* process are naturally occurring, non-pathogenic bacteria. They work within reactors, growing on plastic media in the form of a biofilm. Figure 5 shows this conversion of nitrate to nitrogen gas within a biofilm.

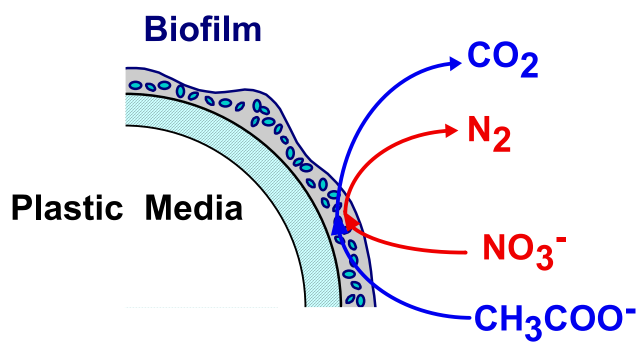



**Figure 5: Denitrification within a Bacterial Biofilm**

The *BioDen™* process uses a mixed population of facultative heterotrophic bacteria to destroy the nitrate molecules. Typically, the bacteria used to inoculate the *BioDen™* reactor system are naturally occurring bacteria that are cultured and enriched from non-contaminated soils or purchased from a recognized producer of such biological products.

The destruction of nitrates is carried out within biological denitrification reactors that incorporate a fixed-film process (Figure 6).

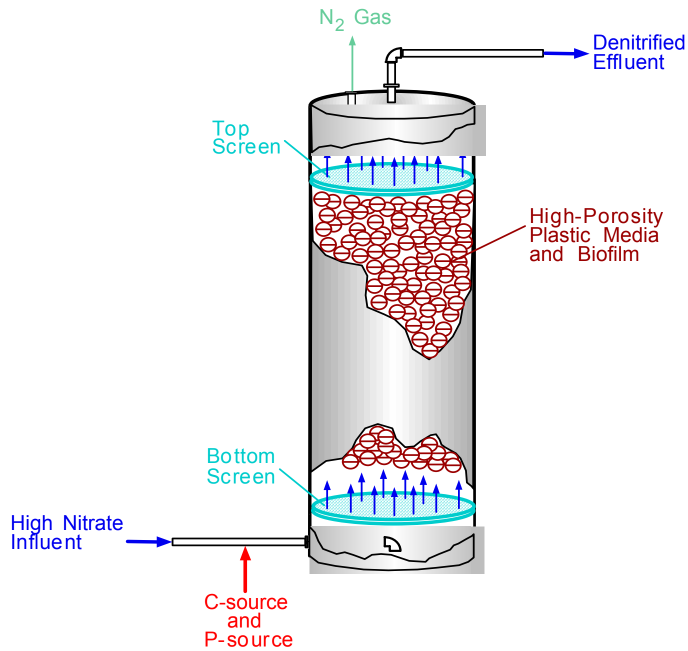



**Figure 6: *BioDen*[TM] Biological Denitrification Reactor**

After the addition of an external carbon and phosphorous source, the raw water flows through reactors filled with a high-porosity, low-density packing material. This packing material provides a large surface area for bacterial attachment while minimizing potential channeling and clogging problems. Additionally, flow through the reactor is upward through the reactor to maximize nitrogen gas ($N_2$) removal. Nitrates diffuse into the attached biofilm and are subsequently converted to nitrogen gas, which is then vented harmlessly out the top of the reactor.

*Reactor Growth Environment: Impact on Bacterial Speciation*

It is important to understand the bacterial growth environment within the reactor system because the growth conditions will affect not only the type, i.e. chemoorganitrophic for example, but also the species of bacteria, i.e. pathogens versus non-pathogens.

The reactor can be conceptually separated into three zones: an anaerobic zone, a microaerophilic zone, and an aerobic zone. These environmental "zones" directly impact the type of bacteria that can survive within each zone and within the entire reactor. Only obligate aerobic bacteria can survive in the aerobic zone while microaerophilic bacteria can only survive in a narrow band where the dissolved oxygen concentration is acceptable for growth. In contrast, facultative bacteria, which can use either oxygen or nitrate as an electron acceptor, can survive throughout the entire length of the reactor.

*Growth conditions for the pathogens of interest.*

The ability to reduce nitrate, food requirements, oxygen requirements, and temperature constraints were used to determine the possibility of growth of the microorganism within the reactor. There are only 2 bacteria that have an estimated greater than 1 in 5 probability of occurring within the denitrification reactor. Even though coliform bacteria have a high probability of being present within the reactor, the estimated survivability of *Shigella* sp. and *Yersinia enterocolitica* is low because these bacteria are not usually found in soils. The protozoa, viruses, and cyanobacteria listed have an extremely low probability of being present in the reactor. The bacteria that have the highest probability of being present in the reactor are: total coliforms (non-pathogenic) and *Pseudomonas aeruginosa* (opportunistic pathogen)

Comparing these results to the occurrence of these bacteria in natural source waters and within treatment plants/distribution systems (Section 4 and Section 5), the probability of appearance of these bacteria in the *BioDen™* reactor effluent is not a large concern. The effect of chlorine on coliform type bacteria and *Pseudomonas aerugenosa* is well documented with very high susceptibilities to chlorine. Therefore, after filtration and chlorination, the system will meet all Federal Drinking water Standards for microbiological quality.

### 2.2.3. Task Outcomes

*Bacteria Evaluation Test Results*

1) Bacteria Species Identification

Denaturing gradient gel electrophoresis (DGGE) analysis was used to determine the species of bacteria in the effluent of the *BioDen™* pilot system located at Suffolk County, New York. The speciation tests identified five dominant species with at least one percent of the total community:

- *Pseudomonas coronafaciens*
- *Pseudomonas chlorophis*
- *Azospirillum sp.*
- *Zoogloea ramigera*
- *Janthinobacterium lividum*

2) Bacterial Information

Analysis of the five dominant species within the system shows that none of the identified species are known human pathogens:

*Pseudomonas coronafaciens*

Cells: straight or curved rods, range 0.5 -1 by 1.5 – 4 μm, gram-negative, strictly aerobic, nitrates not reduced to nitrites or to gaseous nitrogen. This bacterial species is common plant pathogen (phytopathogen) that attacks foliage-causing chlorosis on leaves (Madigan et al., 1997) and is rarely found free in soil (Madigan et al., 1997). This bacteria is not considered a human pathogen.

*Pseudomonas chlorophis*

Cells: straight or curved rods, range 0.5 -1 by 1.5 – 4 µm, gram-negative, can denitrify by aerobic respiration, nitrates reduced to nitrites, nitrous oxide, or to gaseous nitrogen. This bacterial species is relatively common soil microbe that is heterotrophic and capable of denitrification (Bodelier et al., 1997). This bacteria are not considered human pathogen.

*Azospirillum sp.*

Cells: spiral-shaped, range 1 by 2.5 – 3 µm, gram-negative, microaerophilic, nitrogen gas reduced to ammonia with subsequent conversion to organic nitrogen This bacteria is a common nitrogen-fixing bacterium found in natural soils (Han and New, 1998). These bacteria are typically associated with grasses and legumes. This bacteria is not a human pathogen.

*Zoogloea ramigera*

Cells: rod shaped, range 0.5 – 1 by 1 – 3 µm, gram-negative, microaerophilic, nitrates can be reduced to nitrites or to gaseous nitrogen *Zoogloea ramigera* is considered a slime forming bacteria. It is found in soils and many biological systems (Madigan et al., 1997; Rosselló-Mora et al., 1995). This bacteria is not considered pathogenic to humans.

*Janthinobacterium lividum*

This bacterium is also commonly found in soils. It has been used for the degradation of hazardous materials in 2,4-dinitrophenol (Silverstein, personal correspondence). This bacteria is not considered harmful to humans.

Using the above information, it can be stated that the likelihood of the Pseudomonas species identified of being pathogenic is low because *P. coronafaciens* do not denitrify a*nd P. coronafaciens* is rarely found free in soil. It is probable that the predominant denitrifying bacterium within the reactor system is *Pseudomonas chlorophis.* This is consistent with available data showing this bacterium to be very common in soils and its ability to denitrify.

In addition, the results indicate that the bacteria within the reactor are predominantly gram-negative rod or spiral shaped bacteria. The bacteria isolated can occupy various environmental conditions including strictly aerobic, microaerophilic, and facultative conditions.

### 2.2.4. Conclusions and Recommendations

#### 2.2.4.1. Conclusions

- On December 20, 2000, the City of Modesto officially notified researchers with Nitrate Removal Technology of its decision to delay the move forward on the Grayson Biological Denitrification Project. The City will pursue the possibility of installing a 1,000 foot deep well in the area of the Grayson system that might yield water below the nitrate action level. There has been considerable speculation the City staff are extremely reluctant to use microbes to accomplish a potable water treatment goal, even with post-disinfection of the effluent. This is consistent with the misconception by most water treatment professionals' belief that microbial growth during the treatment process is aesthetically objectionable.

We need to overcome this misconception by continuing technology education and field demonstration for broader application/acceptance.

- While EPRI and the researchers view this with acute disappointment, the team was able to secure approval from the California Department of Health Services for a suitable test protocol for this process. As designed, the protocol will yield valuable information for the Department to rule on the efficacy of the biological denitrification treatment system. Eventually, this will result in Department approval of the process for the removal of nitrates from potable water supplies in the State of California.
- Based on discussions with California DHS and other interested parties, the Modesto pilot study will be conducted in two phases. The first phase will consist of a one to three-month demonstration of a 6 to 10 gpm pilot system. The principal goals of the assessment will be to evaluate water quality, and will be focused on the denitrification achieved and the impact on filtration. During Phase 2 of the study, a demonstration system capable of treating 300 gpm or more will be installed and operated. The demonstration system will be used to develop detailed cost data and validation of health safety issues on a full scale commercial size project. Preliminary estimates suggest that biological denitrification compares quite favorably to both ion exchange and reverse osmosis, which are the two current technologies used to remove nitrates today.

#### 2.2.4.2. Commercialization Potential

**Technology Development**

As of early 2001, the EPRI Municipal Water and Wastewater Program has sponsored or managed three different assessments of this technology that have proven its effectiveness. This section summarizes that developmental work

- The initial development of this technology centered on a study by researchers from the University of Colorado in Wiggins, Colorado. That pilot study lasted approximately two years and was the first field demonstration of a process developed by the University of Colorado in Brighton, Colorado from 1989 to 1991. Both towns are located in predominately rural eastern Colorado and rely on groundwater for their drinking water supply. Neither town had the resource nor the skill needed to operate a reverse osmosis drinking water plant.
- The Wiggins study was conducted to: operate a full-scale demonstration facility (with a capacity of 10 to 20 gpm), provide intensive monitoring over several seasons to obtain Colorado Department of Public Health approval, and evaluate process response to a variety of stresses and equipment failures. The results were outstanding.
- The Wiggins study demonstrated the reliability and robust nature of the process. Once steady-state was established, the water nitrate levels fell from 20 – 25 mg/L in the raw water to a range of 2 to 4 mg/L as N. Further, it was found that after an upset the process could be revived quite quickly. For instance, when the carbon source feed pump failed, denitrification could be reestablished within 24 hours after restarting the pump.

- One significant finding from the Wiggins study was the choice of carbon source or carbon substrate. Initially the researchers used food-grade acetic acid. The researchers then switched to food-grade corn syrup. The corn syrup was relatively inexpensive, could be added to potable water, and could be added using simple feed pumps. Unfortunately, this option had unexpected and detrimental side reactions which overcame the positive cost factor. Food grade acetic acid was adopted for future use.

**New York State Pilot Study**

- With the success at Wiggins, Nitrate Removal Technologies (NRT) of Golden, Colorado patented the process under the trade name *BioDen™*. NRT pursued a number of demonstration studies using the technology, including one in Suffolk County, New York that EPRI sponsored. During the testing, the four filter technologies were studied. At the Wiggins testing, the researchers had used only slow sand filters. This study attempted to assess the efficacy of alternative, high-rate filtration options.
- The pilot study demonstrated that the *BioDen™* denitrification system consistently produced water with nitrate levels at 38 percent of the influent levels. Effluent from the BioDen reactors ranged from 1.9 mg/L to 6.8 mg/L but averaged 3.4 mg/L. The average raw water nitrate concentration was approximately 9 mg/L. When coupled with the high-rate filtration system, the *BioDen™* produced safe and high-quality drinking water for turbidity, nitrate, nitrite, and common bacteriological levels such as HPC and fecal coliform.
- While the bag-and-cartridge filter was a failure, the microfiltration techniques proved to be very effective. Both microfiltration systems performed better than the slow sand filters in terms of turbidity removal, removal of coliform bacteria, chlorine demand in the filter effluent, and removal of HPC bacteria. On the other hand, the slow sand filter was more effective at removing both total organic carbon and reducing total trihalomethane formation potential (TTHMFP).
- For small denitrification water treatment systems, a slow sand filter with the simplicity of maintainance, is the proper choice. However, for larger systems or for those drinking water systems in areas with limited land space, the microfiltration systems combined with the *BioDen™* biological denitrification system is an effective means of producing potable water from groundwater supplies polluted with high levels of nitrates.

#### 2.2.4.3. Recommendations

While biological denitrification costs range between $0.55 and $1.40 per 1000 gallons, ion exchange costs from $ 0.55 to $ 1.85 and reverse osmosis costs range from $ 0.60 to $ 5.20 (both per 1000 gallons). The broad range in costs for the conventional treatment technologies is the result of brine disposal costs and electricity costs, which vary depending on the location. In California, these disposal costs and power costs are expected to be on the high side of these ranges. Further, given California's recent power issues, any technology that conserves electricity, such as biological denitrification, will have inherent advantages over those that rely heavily on electricity, such as reverse osmosis. It is recommended that energy comparisons of these technologies be performed on commercial scale to fully assess the energy benefits of biological denitrification.

#### 2.2.4.4. Benefits to California

**Traditional Options**

- In the past, nitrate was removed from drinking water supplies using some form of ion exchange, reverse osmosis, and electrodialysis. Each of these three processes is effective in removing nitrates, but each has significant disadvantages. In ion exchange, the water is pumped through a special medium where a chemical species is exchanged for nitrates absorbed on the media. Under reverse osmosis, the nitrates (and all other ionic species) are essentially strained from the water. Electrodialysis uses an electrical energy to drive the nitrate through special membranes to cathodic plates.
- In addition, all three processes require significant sophistication to operate. This sophistication is typically much greater than what is currently used by most small system operators in the U.S. Perhaps the most significant problem with these alternatives is the wastestreams generated by each processes which produce a concentrated waste-brine which is very difficult to dispose. Currently, in-land disposal of brine is usually limited to discharge to the local wastewater treatment plant, discharge to an evaporation pond, or deep well injection. All three options are costly in terms of either land cost or operating costs.
- The other option most often used by drinking water systems has been to obtain alternative sources. Oftentimes, this entails a significant capital investment in pipelines and new wells or water treatment plant intakes. This option can complicate treatment of a utility's drinking water if the new source has a significantly different chemical make-up than the existing supplies. In addition, the costs associated with new pipelines, easements, permitting and appurtenances can be very high.
- Given the tremendous difficulties of removing nitrate from potable water supplies using conventional treatment processes, a potentially attractive alternative was investigated by researchers from the University of Colorado. This alternative uses a process common to wastewater treatment to remove nitrates, and is known as biological denitrification.

**California's Options**

- Throughout California, nitrate removal options are similar to those described above for the rest of the U.S. However, many water suppliers prefer blending contaminated supplies with low-nitrate water. Table 1 summarizes the costs of the various options.

**Table 1: Summary of Nitrate Treatment Options for California**

| Per 1,000 gallons | Capital Costs | Operating Costs | Brine Disposal | Total Cost |
|---|---|---|---|---|
| RO | $ .44 - .88 | $ 1.10 - 3.00 | $ .40 - 2.60 | $ 1.54 - 6.48 |
| Ion Exchange | $ .24 - 1.18 | $ .46 - .64 | $ .04 - .32 | $ .70 - 2.14 |
| Water Purchase | Varies | $ .Varies | NA | $ .50 - 1.84 |
| BioDen | $ .40 - .90 | $ .50 - .80 | $ .01 - .02 | $ .91 - 1.72 |

- Thus, the majority of California water suppliers try to purchase low-nitrate water, drill new wells, or adopt more traditional treatment technologies. Purchasing low-nitrate water costs from $ 200 to $ 500 per acre-foot (the MWD rate is $431), but prices are expected to continue to rise as California's population grows and the gap between water demand and supply increases. Drilling new wells is often not a viable option because, given the widespread nature of the problem, new well sites are either unavailable or are located at remote distance from the point of use, making this option uneconomical.
- Nevertheless, there continues to be widespread reluctance among drinking water professionals to use microbial techniques in achieving drinking water treatment goals. The speciation described in subsequent chapter was the result of one water utility's reluctance to demonstrate this technology for fear that the microbes could cause problems for both the utility's staff and customers. Interestingly, the speciation work established that the nitrifiers grown in the denitrification reactor are common to the environment and not pathogenic to humans.

## 2.3. Task 2.3 – Solids Removal Technologies

### 2.3.1. MWD Study (Solids Removal Technologies)

#### 2.3.1.1. Objectives

- Evaluate pilot-scale conventional treatment, conventional treatment with ozone/biofiltration, and microfiltration processes as the pretreatment step to membrane-based desalting.
- Evaluate full-scale conventional treatment as the pretreatment step to membrane-based desalting.
- Model the cost savings associated with a 100 million-gallon-per-day (mgd) desalting plant using conventional treatment (both with and without ozone and biologically active filters) versus microfiltration as the pretreatment step.

#### 2.3.1.2. Approach

Experimental methods used involve the selection of: 1) source water; 2) pilot-scale test equipment; 3) full scale test equipment; and 4) analytical methods.

<u>Source feed water</u> used consisted primarily of a 75/25 percent blend of CRW and California State Project water (SPW).

<u>Pilot-Scale equipment</u> consisted of the regular conventional treatment plant, the same conventional plant with ozone and biological filters and the microfiltration unit.

*Conventional treatment plant* was a 60 gpm package plant consisted of a static mixer, flocculation and sedimentation basins, and dual-media (anthracite coal and sand) filtration system.

- Conventional treatment plant with ozone and biological filter.
  The 60-gpm pilot plant was operated with 0.8 to1.2 mg/L ozone dosed prior to the static mixer, and no chlorine was added prior to filtration to allow the filter to ripen biologically. Ozone was supplied by an ozone generator.
- Microfiltration unit
  Pretreatment to the RO was also provided by a 22 gpm microfiltration (MF) unit. The net driving pressure ranged from 6 to 10 psi yielding a filtrate flow rate of 20 gpm at a flux rate of 60 (gal/$ft^2$/day) gfd.
- Three-element membrane test unit
  A pilot-scale RO unit was used to evaluate the pretreatment efficiency of conventional treatment with and without ozone and biologically active filters. Antiscalant was fed just prior to the RO influent. Because of low recoveries (less than 20 percent), no pH adjustment was required.
- 24-Element Membrane Test Unit
  A three-array RO unit was pilot tested during the microfiltration evaluation phase of this task. The RO unit was operated between 85 and 90 percent recovery rates (i.e., for 90 percent water recovery, the permeate flow was 16 gpm and concentrate flow was 2.0 gpm at 98 percent salt rejection) for the duration of the project. Antiscalant and sulfuric acid were added prior to the RO influent to minimize scaling. Prior to testing, the RO membranes were cleaned using an

acidic solution followed by a caustic solution. Additionally, the RO membranes were cleaned when either the normalized flux decreased 15 percent, the differential array pressure reached 30 psi, or a significant increase in salt passage was observed.

<u>Full-Scale Filtration Plants</u>

- The F. E. Weymouth Filtration Plant, located in La Verne, California, is a 520 mgd surface water treatment facility consisting of two rapid mix influent channels, eight flocculation basins, eight sedimentation basins, 48 filters and a 50 million-gallon finished water reservoir. Chemical feeds include alum, cationic copolymer and chlorine. The average filtration rate was 3.0 gpm/$ft^2$. The filter backwash was initiated when any of the three set point parameters were reached: maximum head loss (6.0 ft), filter effluent turbidity (0.2 NTU), or maximum filter run time (48 hr).
- The 520-mgd Robert F. Skinner Filtration Plant in Winchester, California was utilized to study the performance of RO membranes, using either ferric chloride or aluminum sulfate (alum) as the primary coagulants. The study utilized the filtration plant's direct-filtration modules with tri-media filters (anthracite, garnet, and ilmenite sand). Filtration rates for the filters were typically maintained at approximately 6 gpm/$ft^2$.
- Three-Element Membrane Screening Unit - A pilot-scale unit with three parallel pressure vessels was used to evaluate RO membrane performance on conventionally treated water using alum and ferric coagulants. Reverse osmosis membranes tested included: Hydranautics LFC1, ESPA1, and ESPA3, Hydranautics, Oceanside, Calif.; TFC-ULP®, Koch Fluid Systems, San Diego, Calif.; and FilmTec Enhanced LE, Dow Separation Processes, Minneapolis, Minn.. Antiscalant (1.6 mg/L Permatreat 191; Permacare, Fontana, Calif.) was used. Because the unit operated at low recoveries ($<10$ percent), no pH adjustment was required. This system was used solely to evaluate the organic, biological, and/or colloidal fouling potential of conventionally treated water.

*Analytical Methods*

The water quality data of the pretreatment and RO processes were collected in the form of hardness, alkalinity, TDS, major cations and anions, trace metals, particle count, turbidity, temperature, pH, and heterotrophic plate count (HPC) bacteria. A detailed discussion of the methodologies used can be found in MWD's Task Report 2.3 found in the Appendix. All sampling was conducted by Metropolitan's staff. Inorganic and microbial analyses were analyzed at Metropolitan's Water Quality Laboratory in La Verne, Calif.

*Membrane Autopsy*

Upon completion of each pretreatment evaluation phase, the lead RO element was autopsied by Metropolitan personnel. Swatches of membrane material were collected and sent to independent laboratories for microscopic analysis. The following analyses, using Scanning Electron Microscopy (SEM) and the Energy Dispersive Spectroscopy (EDS), were performed by the Scripps Oceanographic Institute in La Jolla, Calif.

Scanning electron microscopy provides a magnified visual picture of the membrane surface. Energy dispersion spectroscopy analysis provides an elemental analysis of elements with atomic numbers greater than 12 (magnesium). Used together, SEM and EDS analyses were used to judge the degree and composition of foulant materials on the membrane surface.

#### 2.3.1.3. **Outcomes**

Pilot-Scale Testing

- Microfiltration produced water containing lower particle counts, turbidity, and silt density index (SDI) than either conventional treatment or conventional treatment with ozone/biofiltration. However, all three pretreatments produced waters with median turbidity of less than 0.1 NTU and median SDI of less than or equal to 3, which were lower than the RO membrane manufacturer's recommendations (less than 1 NTU and less than 5 SDI, respectively). Little variation between influent and effluent solute concentrations was observed for each of the three pretreatment processes.
- Pretreatment using conventional treatment showed the poorest RO performance in terms of maintaining stable flux over time, followed by conventional treatment with ozone/biofiltration, and finally microfiltration. The average flux for the RO membranes using conventional treatment, conventional treatment with ozone/biofiltration, and MF was 0.28, 0.35, and 0.23 gfd/psi, respectively. The lower specific flux for the microfiltration pretreatment phase was due to operation with different RO elements and not indicative of pretreatment performance. Cleaning frequencies for the RO membranes were once per month and once every two months for conventional treatment and conventional treatment with ozone/biofiltration, respectively. The RO membranes only required chemical cleaning after three months of operation when using MF pretreatment due to purposely introducing a foulant into the system. Salt rejection of the membranes for all three pretreatment technologies ranged from 97 to 99 percent

Full-Scale Testing

*Testing with Aluminum Sulfate*

A total of five different RO membranes were tested at the F.E. Weymouth Filtration and Robert F. Skinner Filtration plants using alum coagulation and chloramines. Repeated testing with multiple RO elements revealed rapid deterioration in specific flux (up to 60 percent over 100 hrs of operation), as well as progressive reductions in salt rejection (typically 3 to 4 percent over 500 hrs of operation). Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis of the fouled membranes revealed that the foulant was primary aluminum hydroxide and aluminum silicate materials.

*Testing with Ferric Chloride*

In contrast to the RO data using alum coagulation that showed declining specific membrane flux, the specific flux data when using ferric chloride and chloramines increased over time for all membranes. However, salt rejection for each membrane decreased significantly during testing. These data suggested that the RO membranes were physically degrading over time. SEM and EDS data showed that the foulant was inorganic in nature and comprised mainly of aluminum, iron, and silica. The RO membranes may have been degraded by residual iron catalyzing a chlorine-amide reaction on the membrane surface, despite the chlorine being present as chloramines.

*Economic Evaluation*

Preliminary cost estimates for retrofitting a 300-mgd conventional filtration plant using split-flow treatment showed that utilizing the existing conventional treatment plant as the pretreatment step to a 100-mgd RO system was the lowest cost option ($0.39/1000 gal of finished water). While providing excellent pretreatment for the RO system, MF showed at least a 10 percent higher cost to retrofit an existing facility using split-flow treatment with reverse osmosis ($0.44/1000 gal) due to the need to install additional pretreatment facilities. Using this criterion, the project goal of reducing the overall treatment costs by 10 percent was met using conventional treatment as the pretreatment step to RO. The addition of ozone and biological filtration lowered the RO capital costs, but increased the overall treatment costs to $0.52/1000 gal of finished water, again due to the need to install new pretreatment equipment. While using existing conventional treatment plants can potentially save millions of dollars in capital expenditures, the RO costs associated with using conventional treatment are significantly higher than with using either microfiltration or conventional treatment with ozone/biofiltration. Additionally, high membrane fouling rates associated with using conventional treatment may reduce this option's feasibility.

#### 2.3.1.4. Conclusions and Recommendations

**Conclusions**

*Pilot-Scale Results*

Despite each pretreatment tested (conventional treatment with and without ozone biofiltration and microfiltration) providing high-quality effluent water, dramatic differences in RO performance was observed. The conventional treatment phase required chemical cleaning three times within the three-month test period due to organic and biological fouling that resulted in a loss of specific flux. However, the performance of conventional treatment was improved through the addition of pre-ozonation and operating the filters biologically active. Despite being operated at higher flux, conventional treatment with ozone/biofiltration slowed the RO membrane rate of fouling by a factor of 2. The improved performance for biofiltered water may have resulted from the stabilization of the (natural organic matter) NOM through the ozonation/biofiltration process. Microfiltration provided the highest quality water to the RO process and thus resulted in the lowest cleaning frequency.

*Full-Scale Results*

Testing with full-scale conventional drinking water treatment showed differing results from the pilot-scale testing. Conventional treatment using both aluminum sulfate and ferric chloride coagulation resulted in adverse membrane performance that would hinder full-scale implementation of RO technology. During RO testing using alum coagulation (6 to 8 mg/L), alum residuals (aluminum hydroxide) and colloidal clay materials (aluminum silicates) rapidly accumulated on the membrane surface and caused a loss in flux. However, salt rejection was largely unaffected. In contrast to results obtained using alum, when ferric chloride (4 to 5 mg/L) was used as the primary coagulant, the specific membrane flux increased at the same time the salt rejection decreased. It was theorized that the residual iron in the pretreatment effluent aided in the deacetylation reaction on the membrane surface that resulted in membrane degradation, though the exact reaction pathway was not determined.

*Economic Evaluation*

The project goal of reducing the overall treatment costs by 10 percent was met using conventional treatment as the pretreatment step to RO. However, high membrane fouling rates associated with using conventional treatment may reduce this option's feasibility. The addition of either ozone and biological filtration or MF lowered the RO capital costs, but increased the overall treatment costs due to the need to install new pretreatment equipment.

**Commercialization Potential**

To ensure commercial viability and the implementation of newly developed technology, project results will be published in refereed journals and presented at national conferences to water and wastewater industry professionals. The purpose of publications/presentations is to disseminate technical information to a broad range of industry representatives. Results for this study can then be incorporated into ongoing research and development activities throughout California, and the country. In addition, suppliers of membrane and membrane-related technologies will develop comparable products to maintain competitiveness in the industry.

**Recommendations:**

Additional applied research is still needed to optimize the conventional treatment process with and without ozone/biofiltration. A better understanding of the improved performance under the ozone/biofiltration pretreatment and its effects on the NOM of the water are needed. Additional work is also needed to better understand the full effects of the interaction of different chemicals such as: coagulants (i.e. ferric, alum), disinfectants (i.e. chloramines), and antiscalants on the surface of the membrane.

It is recommended that for utilities that are designing new desalination plants, microfiltration is the optimal pretreatment technology which provides the best feed water for RO membranes, while minimizing fouling. However, additional work with conventional treatment processes may help water treatment plants use existing infrastructure as pretreatment to RO, thereby saving capital costs.

#### 2.3.1.5. Benefits to California

This task is an integrated part of a larger MWD program, the Desalination Research and Innovation Partnership (DRIP). The overall goal of the DRIP program is the cost-effective demineralization of the Colorado River water (CRW), as well as other water sources. Results from this study, as well as other interrelated studies, will enable local municipalities to adopt desalination technologies to treat current and previously unusable potable water supplies.

The primary economic benefit is the reduction of societal damages to the public and private sectors due to high salinity of Colorado River water. An additional benefit is the reduction of energy usage to reduce the TDS of CRW over currently available technologies. These are broad societal, or public interest, benefits that conform to PIER goals. Each acre-foot of CRW treated by technologies derived from this study would require less energy than current desalination practices, or through importing low salinity water from Northern California. Additionally, technologies evaluated during this project may be applicable to other source waters in California. These include municipal wastewater, brackish groundwater, and agricultural drainage water.

### 2.3.2. OOWD Study (Solids Removal Technologies)

#### 2.3.2.1. Objectives

This study was initiated to identify correlations between membrane and module properties and membrane fiber failure (i.e., loss of integrity). Specifically, module potting technique, membrane symmetry, fiber modulus of elasticity, fiber thickness, module flow pattern (inside-out or outside-in), and membrane material are being investigated. The approach combines mathematical modeling of structure-fluid interactions with analysis of membrane failure made at the Orange County Water District (OCWD) pilot- and demonstration-scale facility.

### 2.3.2.2. Approach

**Experimental Approach**

The performance of five membrane modules were tested (Table 2). Fibers from two of these modules were supplied for scanning electron microscope (SEM) analysis and tensile testing. Additionally, fibers from three membrane modules that were not tested for performance were supplied for SEM analysis and tensile testing. Therefore, a total of five fibers underwent SEM analysis and tensile testing.

**Table 2: Microporous Membrane and Module Properties**

| Membrane | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| | PM 882 | PM 100s | PM | PE | PAN 13 | PAN 80 | PVDF | PP pressure | PP submerse |
| **Type** | UF | UF | UF | MF | UF | UF | MF | MF | MF |
| **Material** | PS | PS | PS | PE | PAN | PAN | PVDF | PP | PP |
| **Symmetry** | A | A | A | S | A | A | S | S | S |
| **Pore Size** | | 100,000 MWCO | 100,000 MWCO | 0.1 μm | 13,000 MWCO | 80,000 MWCO | 0.1 μm | 0.2 μm | 0.2 μm |
| **Flow** | inside-out | inside-out | inside-out | outside-in | outside-in | outside-in | outside-in | outside-in | outside-in |
| **Potting Type** | static | static | dynamic | static | dynamic | dynamic | dynamic | dynamic | dynamic |
| **Elastomer** | | no | no | yes | yes | yes | no | no | no |
| **Performance Testing** | Pilot scale | Pilot scale | No data | No data | No data | No data | Demo scale | Pilot scale | Pilot scale |
| **Fiber Supplied?** | no | yes | | yes | yes | yes | yes | no | |

Several SEMs images were created for the five membrane fibers. Surface and cross-sectional images of the fibers were evaluated. The hollow fiber symmetry and thickness were confirmed using the cross-sectional images.

Tensile testing of the hollow fiber membranes was performed using Instron testing equipment. The purpose of this testing was to determine how strong the fibers are and how much deformation can be expected given a certain load. In the test, the membrane fiber is held by grips on either end and the elongation is monitored as the fiber is pulled in tension at a constant rate. The result is a load-elongation curve. By normalizing this curve for the fiber geometry (i.e., dividing the load by the original cross-sectional area of the sample and dividing the elongation by the initial length), a stress-strain curve for each membrane fiber is developed. The modulus of elasticity is then determined by the slope of the stress-strain curve in the elastic region. The modulus of elasticity (or Young's modulus) represents the stiffness of the material, or its resistance to elastic strain. This manifests itself as the amount of deformation in normal use below the yield strength.

In the experimental portion of the investigation, clarified secondary effluent provides feed water for the pilot plants. Modules A-G are backwashed at 20-minute intervals for 2 to 3 minutes with MF/UF permeate. In addition, some of the membrane is scoured with air for two minutes at six-hour intervals. Modules H and I are backwashed with air followed by a feed flush every 18 to 20 minutes.

*Modeling Approach*

The membrane module is being modeled using ADINA, Automatic Dynamic Incremental Nonlinear Analysis, which models time-dependent structure-fluid interactions using finite element analysis. The structural model, ADINA, is used to determine structural deformations. The structural model is composed of a porous pipe, representing the hollow fiber, and a block, representing the potting material. Boundary conditions for the porous pipe include translational degrees of freedom in the transverse directions, while the longitudinal direction has been fixed. It is assumed that rotations do not occur. The potting material has been fixed in all directions. Pressure and distributed loading on the structures are being considered. A preliminary model depicting fracture (large displacement/large strain type of analysis) at the junction between the pipe and potting material is being undertaken in order to model breakthrough. The fluid model, ADINA-F, is used to determine fluid flow. The fluid model is composed of a block of fluid surrounding the pipe. The fluid is assumed to have constant properties, (i.e., constant viscosity, density, and surface tension coefficients). The boundary condition is a prescribed fluid velocity. Iterative solutions are obtained for both the structural and the fluid models. Within one time step, ADINA-F is run until convergence. The loads on the structure due to fluid flow are then passed onto the ADINA model, which is run until it converges. The new structural geometry is then passed back to the ADINA-F model. A user-specified convergence criterion (fracture criteria) within a specified tolerance determines the end of the simulation.

#### 2.3.2.3. Outcomes

*SEM Analysis*

Figure 7 shows SEM images for the five fibers. Although the thickness was difficult to measure exactly, the approximate thickness estimated from the difference between the outside radius and inside radius of the fiber was confirmed for each of the samples. Additionally, the PM-100, PAN 13000, and PAN 80000 were found to be asymmetric and the PE and PVDF fibers were found to be symmetric.

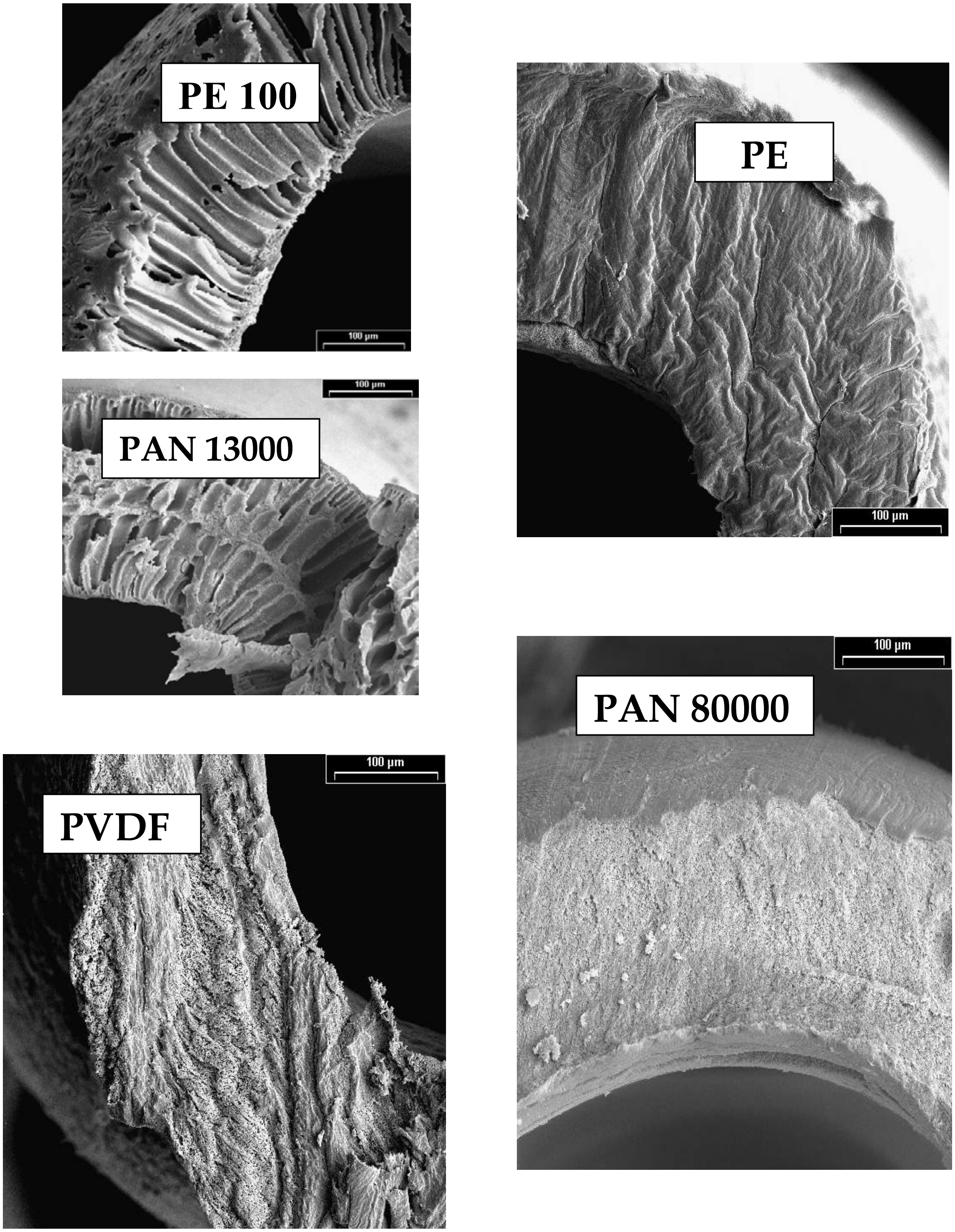



**Figure 7: SEM Images of the Five Hollow Fiber Membranes**

*Tensile Tests*

The strongest fiber is the PAN 80000. The high strength of the PAN 80000 was anticipated prior to testing. In making this fiber, the phase inversion process was slowed down to allow for more partitioning of the solvent and consequently, more void space. The intention of the manufacturer was to create a stronger fiber. The weakest fiber is the PE. The PAN 13000, PVDF, and PM fibers have intermediate strengths

*Performance Analysis*

The PM-882 module had the lowest performance of the five membrane modules that were tested. This module experienced many sudden drops in pressure and had to be cleaned frequently. The PM-100 (static) module also performed poorly, although marginally better than the PM-882 module. Frequent cleaning, low transmembrane pressure, and coliform breakthrough were the main problems with this membrane. The PP pressure module performed better than the PM-882 and PM-100 modules, but not as good as the PP submersible module. Both the PP submersible module and the PVDF module had the highest performance. Both modules were operated for long periods (approximately three weeks) between cleanings. Over the lifetime of the PVDF module, no fiber breakages were detected.

The boundary conditions allow translational movement in the y and z directions, but no translational movement in the axial (x) direction. Rotational degrees of freedom have been fixed in all directions. The fluid structure interface boundary includes the outer and inner faces of the fibers and the top of the elastomer. Pressure loading occurs on the outer fiber faces and the top surface of the elastomer.

#### 2.3.2.4. Conclusions and Recommendations

**Conclusions**

- Correlations between membrane and module properties and membrane fiber failure (i.e., loss of integrity) were difficult to make because only two membrane fibers (the PM100s and PVDF fibers) underwent both materials testing and performance testing.
- Preliminary modeling results found the existence of additional stresses at the fiber/potting juncture which might possibly lead to the formation of fractures. Further modeling was impeded by limitations of the ADINA software.
- Although several ADINA updates were received over the course of the investigation and enhanced capabilities were to be forthcoming, the software never reached the initially stated potential. For this reason, current and future modeling efforts are focusing on more advanced software, ANSYS.

**Commercialization Potential**

Information acquired from the study of microporous membrane fiber integrity will assist with the development and manufacture of longer lasting MF and UF membranes and modules for the reclamation market. Reductions in operation and maintenance costs associated with loss of membrane fiber integrity will allow this technology to be more competitive with other less effective existing technologies.

**Recommendations**

- Future efforts should include the evaluation of immersed hollow fiber membranes as well as evaluation of the impact of backwashing (using both air and water) on hollow fiber membrane integrity. The immersed hollow fiber membranes have been found to delaminate or crack in the area where the hollow fiber meets the potting material.
- The current model for pressure-driven membranes could be modified for the suction-driven membranes. Similar to the current investigation, results from the structure-fluid model would be combined with analysis of membrane failure for OCWD demonstration-scale submersible membrane systems.
- The process of backwashing hollow fiber membranes may be responsible for the widening of the pores or the weakening of the material properties of hollow fiber membranes. To investigate the effects of backwashing on hollow fiber membrane performance and integrity, the structure-fluid model would be further modified to be able to evaluate the effects of air and water backwashing. Results from this model would again be compared to observations and measurements taken at the OCWD pilot- and demonstration-scale facility.

#### 2.3.2.5. Benefits to California:

Preventing microporous fiber breakage will have a significant effect on water treatment and wastewater reclamation in California and throughout the world. The performance of reverse osmosis membranes in indirect potable reuse and the efficacy of disinfection processes (chlorination and ultraviolet irradiation) in direct non-potable reuse are directly dependent on MF and UF fiber integrity.

## 2.4. Task 2.4 – Salinity Removal Technologies

### 2.4.1. MWD Study (Salinity Removal Technologies)

#### 2.4.1.1. Objectives

- Investigate the performance of experimental RO membranes and NF membranes. Low-fouling and low-energy RO and NF membranes were evaluated to determine flux and selectivity for Colorado River water desalting;
- Evaluate the long-term fouling rate of RO membranes using conventionally pretreated water. Cleaning frequency, and flux recovery after chemical cleaning were characterized. Reverse osmosis elements from three different manufacturers were evaluated to determine their potential for fouling;
- Determine potential cost savings using experimental membrane flux and salt rejection data; and
- Evaluate various commercial and generic antiscalants to prevent scale formation during RO treatment of Colorado River water.

#### 2.4.1.2. Project Approach

*Commercial Membrane Testing*

A total of five RO membranes (four experimental [RO1, RO3 through RO5] and one commercially available [RO2]) were evaluated on the pilot-scale using conventional treatment with either aluminum sulfate or ferric chloride coagulation as the pretreatment step. The RO membranes were operated to gauge not only water production (specific flux) and salt rejection characteristics of the membranes, but their fouling behavior using conventionally treated water. Data collected during these tests included flows, pressures, conductivity, and water quality.

In addition to RO membranes, a total of seven experimental NF membranes were evaluated. Each experiment was run using a closed-loop, membrane-test unit until steady-state performance conditions were reached (approximately 3 to 5 days). For evaluating specific flux and salt rejection of each membrane, several membranes were also tested to determine the effects of changing salinity, pH, and ion size on salt rejection. Data collection was similar to that during RO testing.

*Commercial and Generic Antiscalant Testing*

Eight commercial antiscalants and six generic antiscalants were evaluated on the bench-scale to determine their efficacy for scale inhibition. The dosage for each commercial antiscalant was determined using the antiscalant vender's software and Colorado River water quality data. The chemical dosage for each of the generic antiscalants was based on published data and stoichiometric modeling. Each antiscalant was evaluated using a closed-loop, bench-scale test unit using spiral-wound RO membranes at 95 percent water recovery to enhance scale formation. The water quality data of the pretreatment and RO processes were collected in the form of hardness, alkalinity, TDS, major cations and anions, trace metals, particle count, turbidity, temperature, and pH. Additional data collected included feed and concentrate flows and pressures, influent and effluent conductivity, and scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) of the membrane surface.

### 2.4.1.3. Project Outcomes

*Pilot-Scale Evaluation of Reverse Osmosis and Nanofiltration Membranes*

Table 3 provides a summary of the operating parameters for the membranes tested during this study. Of the five RO membranes evaluated during this study, RO1 (Dow Separation Processes, FilmTec Enhanced LE) provided the highest specific flux (0.37 gfd/psi) while still maintaining high salt rejection (98.8 percent). Performance data for NF membranes provided a wider range of variation in water production and salt rejection properties than RO membranes. While NF membranes generally provided high specific flux and lower salt rejection than the RO membranes tested, membrane NF1 (Dow Separation Processes, FilmTec NF90) showed comparable specific flux and salt rejection (0.36 gfd/psi and 98.6 percent, respectively) to that of RO1.

**Table 3: Summary of Membrane Performance**

| Code | Membrane | Normalized Flux (gfd)* | Specific Flux (gfd/psi) | Nominal Salt Rejection (percent)† |
|---|---|---|---|---|
| ***Reverse Osmosis Membranes‡*** | | | | |
| RO1 | FilmTec Enhanced LE | 20.5 | 0.37 | 98.8 |
| RO2 | Koch Fluid Systems TFC-ULP® | 16.4 | 0.22 | 93.9 |
| RO3 | Hydranautics LFC1 | 12.2 | 0.20 | 98.6 |
| RO4 | Hydranautics ESPA3 | 18.7 | 0.26 | 99.1 |
| RO5§ | Hydranautics ESPA1 | 14.5 | 0.21 | 99.0 |
| ***Nanofiltration Membranes***** | | | | |
| NF1 | FilmTec NF90 | 23.2 | 0.36 | 98.6 |
| NF2 | FilmTec NF200 | 18.0 | 0.24 | 82.3 |
| NF3 | Hydranautics Prototype CTC50 | 24.7 | 0.44 | 54.5 |
| NF4 | Koch Fluid Systems SR1 | 24.5 | 0.30 | 64.5 |
| NF5 | Koch Fluid Systems SR2 | 25.6 | 0.63 | 52.5 |
| NF6 | TriSep TS80-TSA | 21.8 | 0.28 | 62.6 |
| NF7 | TriSep XN40-TZF | 18.8 | 0.24 | 97.8 |

* Normalized to 25ºC
† As measured by conductivity
‡ Pretreated using conventional treatment with alum
§ Pretreated using conventional treatment with ferric chloride
** Pretreated using microfiltration

Ion hydrated radius and solution pH had a direct impact on the salt rejection behavior of NF membranes. Generally, as the hydrated radius increased (e.g., from sodium to sulfate), the rejection of that ion also increased. Additionally, operation at low pH conditions increased NF membrane salt rejection through chemically tightening of the membrane surface.

*Economic Evaluation of Reverse Osmosis and Nanofiltration Membranes*

When compared against a currently available commercial RO membrane (RO2), each of the four experimental RO membranes studied improved overall membrane systems costs by at least 15 percent, thereby meeting the project goal to reduce the membrane systems cost by 10 percent. Of the RO membranes tested, RO1 demonstrated the highest specific flux (0.37 gfd/psi) while still maintaining excellent salt rejection (98.8 percent). These two factors resulted in RO1 showing the greatest cost savings (20 percent) over current commercial RO membranes. Two of the NF membranes tested (NF1 and NF7) demonstrated superior performance in terms of both specific flux and salt rejection over a current commercially available ultra-low-pressure RO membrane, resulting in a 19 and 14 percent cost savings, respectively.

In order to minimize the capital and O&M costs for a membrane system, membrane selection plays a vital role. The effects of inherent membrane properties are two fold: 1) as operating pressure decreases, so too does the operation and maintenance (O&M) cost component due to reduced energy consumption; and 2) as salt rejection increases, the capital cost component decreases due to less treated water needing to be blended to achieve the target TDS value. However, the ultimate selection of an appropriate membrane is predicated on the specific application's water quality and quantity goals.

#### 2.4.1.4. Conclusions and Recommendations

**Conclusions**

With the development of polyamide membranes, not only has the operating pressures for membrane systems decreased, but the water production per psi has also increased substantially. However, future increases in energy savings will not be as dramatic due to the approaching physiochemical limits for driving pressure.

Currently, NF membranes operate at significantly higher flux rates than RO membranes, but exhibit poorer salt rejection.

This project only evaluated a small fraction of the total number of antiscalant types available for municipal water treatment. In order to facilitate information exchange between research groups, a standardized antiscalant test protocol needs to be developed. A primary concern with antiscalant testing is achieving representative water quality conditions that mimic those found in full-scale treatment plants at a given water recovery. Closed-loop membrane testing, while inexpensive, may not provide representative water quality conditions and single-pass, multi-array membrane systems are not only expensive but have high water flow rate demands (up to 20 gpm).

**Recommendations**

Further research is needed to wed the high water production of NF membranes with the high salt rejection of RO membranes.

Additional research is needed to develop next generation membranes such that they are either chlorine tolerant to prevent biofouling or exhibit unique surface charge characteristics that prevent particle and bacterial adhesion, or even scaling.

Smaller, single-pass membrane test systems need to be developed.

A standardized protocol for interpreting RO membrane and water quality data to judge antiscalant effectiveness needs to be developed.

Currently, NF membranes operate at significantly higher flux rates than RO membranes, but exhibit poorer salt rejection. Further research is needed to combine the high water production of NF membranes with the high salt rejection of RO membranes.

To facilitate information exchange between research groups, a standardized antiscalant test protocol needs to be developed.

A primary concern with antiscalant testing is achieving representative water quality conditions that mimic those found in full-scale treatment plants at a given water recovery. Closed-loop membrane testing, while inexpensive, may not provide representative water quality conditions and single-pass, multi-array membrane systems are not only expensive but have high water flow rate demands (up to 20 gpm). Therefore, smaller, single-pass membrane test systems need to be developed.

Additionally, a standardized protocol for interpreting RO membrane and water quality data to judge antiscalant effectiveness needs to be developed.

**Commercialization Potential:**

To ensure commercial viability and the implementation of newly developed technology, project results will be published in refereed journals and presented at national conferences to water and wastewater industry professionals. The purpose of publications/presentations is to disseminate technical information to a broad range of industry representatives. Results for this study can then be incorporated into ongoing research and development activities throughout California, and the country. In addition, suppliers of membrane and membrane-related technologies will develop comparable products to maintain competitiveness in the industry.

#### 2.4.1.5. Benefits to California:

This task is an integrated part of a larger program; the Desalination Research and Innovation Partnership (DRIP). The overall goal of the DRIP program is the cost-effective demineralization of CRW, as well as other water sources. Results from this study, as well as other interrelated studies, will enable local municipalities to adopt desalination technologies to treat current and previously unusable potable water supplies.

The primary economic benefit of the DRIP program is the reduction of societal damages to the public and private sectors due to high salinity of Colorado River water.

An additional benefit is the reduction of energy usage to reduce the TDS of CRW over currently available technologies. These are broad societal, or public interest, benefits that conform to PIER goals. Each acre-foot of CRW treated by technologies derived from this project would require less energy than current desalination practices, or through importing low salinity water from Northern California.

Technologies evaluated during this project may be applicable to other source waters in California, including municipal wastewater, brackish groundwater, and agricultural drainage water.

### 2.4.2. OCWD Study (Salinity Removal Technologies)

#### 2.4.2.1. Objectives

*Background & Overview*

The Groundwater Replenishment (GWR) System is a water supply project jointly sponsored by the Orange County Water District (OCWD) and Orange County Sanitation District (OCSD). The GWR System will supplement existing water supplies by providing a new, reliable, high-quality source of water to recharge the Orange County Groundwater Basin (the Basin) and protect the Basin from further degradation due to seawater intrusion. By recycling water, it will also provide peak wastewater flow disposal relief and postpone the need for OCSD to construct a new ocean outfall by diverting treated wastewater flows that would otherwise be discharged to the Pacific Ocean.

The processes used to treat secondary clarified treated wastewater include microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) disinfection. Part of the scope of OCWD's research under the grant from the California Energy Commission was to investigate salinity removal technologies. In the GWR system, salinity removal occurs in the RO process. Three issues were addressed at OCWD. These included: 1) studying and developing new RO membranes that are resistant to chlorine; 2) investigating nitrification and denitrification of RO brine (waste); and 3) testing the RO and MF processes on the wastewater treatment side.

*Project Objectives*

The objectives of this research were to study RO membranes' performance using different materials as well as feed sources. Part of the research examined treatment methods and options for the brine concentrate generated from the process. Each of the three projects had a different objective.

#### 2.4.2.2. Project Approach

**A. Chlorine Tolerant Membranes**

This project evaluated the performance of a newly developed reverse osmosis (RO) membrane for its ability to treat secondary municipal wastewater.

The development of the polyamide (PA) thin-film composite (TFC) reverse osmosis membrane has successfully enabled water producers to treat a variety of water sources to near distillation quality. Despite the high quality of the water produced by this process, TFC membranes are prone to both colloidal and biological fouling, which both serve to limit the effectiveness of this treatment process. In treating high biologically active wastewaters, membrane biological fouling (biofouling) is often times one of the most pronounced limitations. Numerous and costly pretreatment measures must be carried out in an effort to limit the onset of membrane biofouling. Chlorine and other disinfectants are commonly introduced into the feedwater to limit the occurrence of biological fouling. While this practice is generally effective, it can result in degradation of TFC membranes, which are susceptible to chemical attack by strong oxidizing agents such as chlorine.

The performance of a chemically tolerant, low-fouling reverse osmosis (RO) membrane was evaluated at the Orange County Water District (OCWD) for its ability to treat clarified secondary municipal wastewater effluent. Testing of the CPTC membrane was conducted using two different plant feedwaters produced at OCWD: Water Factory 21 and Green Acres Project (GAP). Membrane performance was compared to that of commercially available TFC membranes.

**B. Brine Disposal**

Recycled water has become one of the significant resources used to replenish the existing water bodies, especially in the states where the production of sufficient water of high quality cannot meet the demand of growing population. Among the technologies employed to obtain recycled water are membrane processes such as microfiltration, ultrafiltration, and reverse osmosis. Recycled water passed through a reverse osmosis membrane is considered highly pure and safe for use.

It is important to determine the disposal or treatment strategies for brines (groundwater supplies with varying salinity and contaminant concentrations) ahead of time during the planning stage of a membrane purification plant, as it may become a problematic issue later.

Fluidized Bed Biofilm Reactors charged with Granular Activated Carbon (FBBR-GAC) were chosen as a promising technology for the nitrification and denitrification of reverse osmosis brine concentrates to remove nitrates and sulfates. This research would also create a model to describe the process dynamics and implement inexpensive pilot-scale testing. Several batch experiments were conducted to find the optimum environmental parameters for the highest possible removal efficiency. Additionally, a series of experiments were conducted to predict the denitrification efficiency of the FBBR-GAC column and to verify the model.

**C. IMANS™**

The GWR System will treat secondary wastewater effluent, currently discharged to the ocean, to produce high-quality water for recharge of the Orange County groundwater basin and injection into a seawater intrusion barrier.

Phase 1 of the GWR project is presently in the preliminary design stage and is due to be operational in 2003. Phase 1 will produce 70 mgd of high quality, low salinity product water, while the three-phase GWR project will ultimately produce about 150 mgd of high quality reclaimed water by 2020.

The Phase 1 treatment system will adopt the current state-of-the-art approach to wastewater reclamation. This includes full secondary wastewater treatment, followed by MF, RO, and UV disinfection to produce high-quality water. There will also be a final UV disinfection step.

Phases 2 and 3 of the GWR project have not yet been defined, and they present a number of different challenges including:

a shortage of land, high costs for additional secondary wastewater treatment facilities, and costs associated with the disposal of large quantities of biosolids.

This report summarizes the novel treatment approach, the pilot processes tested, and the results obtained from the pilot testing. Also presented is a cost estimate and a comparison for full-scale facilities based on the IMANS™ approach and the current conventional state-of-the-art approach to water reclamation. A section of the report also provides conceptual information on the possible approach of using the MF product water from the IMANS™ system for direct discharge to the 78-inch ocean outfall.

The purpose of the preliminary evaluation of the IMANS™ process is two-fold:

- To determine the technical feasibility of operating the new process combination to treat primary effluent to produce a high quality re-usable water suitable for ground water injection and recharge, and,
- To evaluate and compare the cost-effectiveness of the IMANS™ approach with the state-of-the-art process combination that includes full secondary wastewater treatment followed by MF and RO

#### 2.4.2.3. Project Outcomes

**A. Chlorine Tolerant Membranes**

After running the developed membranes in a flat sheet membrane test unit, results were compared and correlated with computer modeling results. Membrane performance of the new membrane was found to be equal, or superior to traditional commercial RO membranes operated simultaneously at OCWD. Water quality was comparable while the total product water production was generally greater than the commercial membranes. The rate at which water production (or flux) declined was also generally lower than the commercial membranes.

It has been successfully shown that membrane separation processes can successfully treat a variety of challenging water types. Commercial TFC membranes in the marketplace lack chemical tolerance to such oxidants as chlorine. A chemically tolerant, low-fouling TFC membrane could quickly expand in the current membrane environment.

**B. Brine Disposal**

The FBBR-GAC system has proven efficient both in terms of process and energy consumption for the denitrification and sulfate reduction of brine concentrates. The optimum operating parameters were determined in this research. Most importantly, preliminary laboratory-scale experiments revealed that the FBBR-GAC process is capable of removing approximately 45% of sulfate and 100% nitrate.

**C. IMANS™.**

The initial testing of the IMANS™ process approach for wastewater treatment combined with water reclamation has shown promising results in terms of both sustainable performance and cost effectiveness. Potential capital cost savings and significant O&M cost savings are predicted for an IMANS™ approach compared with the conventional approach of using membranes to treat secondary wastewater effluent. This has established the technical feasibility of the IMANS™ process combination, even when using a six-year-old MF pilot.

#### 2.4.2.4. Conclusions and Recommendations

**A. Chlorine Tolerant Membranes**

*Conclusions*

Long-term performance of the CPTC membrane was equal, or superior to traditional commercial membranes. While still in its adolescence, the CPTC membrane looks promising as a membrane that could successfully treat high fouling water sources without compromising membrane integrity and performance due to fouling and chemical degradation.

*Commercialization Potential*

Membrane treatment technologies are continually expanding as locations within the United States and around the world are witnessing substantial population growth and corresponding increases in water demand. This is particularly evident when noting the expansion of the membrane technology market, which is estimated to have increased from $363 million in 1987 to over $1 billion in 1997.

Commercial TFC polyamide RO membranes in the marketplace lack the chemical stability to oxidants such as chlorine. A chemically tolerant TFC membrane could quickly expand in the marketplace since most treatment facilities already operate TFC polyamide membranes.

*Recommendations*

The successful development and widespread implementation of a new polymer membrane is a timely process. Since the CPTC membrane is still in its adolescence, more testing would be required to determine the practicability of this membrane as an alternative to conventional TFC membranes in treating high fouling water and wastewater sources.

**B. Brine Disposal**

*Conclusions*

The optimum temperature range for the denitrification was determined to be between 20$^{o}$C and 40$^{o}$C. The total dissolved solid (TDS) concentration had insignificant effect on the denitrification rate. Preliminary laboratory-scale experiments revealed that the FBBR-GAC process is capable of removing approximately 45% of sulfate and 100% nitrate.

*Commercialization Potential*

A predictive model was developed for performance forecasting and up-scaling of the FBBR-GAC process. The preliminary modeling simulation/prediction results are encouraging. Nonetheless, more studies are underway to upgrade the model.

*Recommendations*

It is recommended that the FBBR-GAC process be further investigated in laboratory scale as well as in pilot scale in order to assess its energy efficiency and cost-effectiveness. Sulfate reduction is an additional advantage of the FBBR-GAC system described above. However, more investigation is needed in order to upgrade the system for better sulfate removal. Additionally, a model may be developed for the biological removal in dual-substrate systems (in this case, nitrate and sulfate). Furthermore, detailed experimentation is needed to formulate a model that predicts simultaneous nitrate and sulfate removal in such systems.

**C. IMANS™**

*Conclusions*

The initial testing of the IMANS™ process approach for wastewater treatment combined with water reclamation has shown promising results in terms of both sustainable performance and cost effectiveness. Potential capital cost savings and significant O&M cost savings are predicted for an IMANS™ approach compared with the conventional approach of using membranes to treat secondary wastewater effluent. This has established the technical feasibility of the IMANS™ process combination, even under challenging test conditions such as use of a six-year-old MF pilot. Although not quantifiable in our study, it is expected that significant energy savings can be derived from this process since the secondary wastewater treatment by aeration (which contributes to over 50% of the total energy use) would not be needed.

Elimination of the secondary wastewater treatment step, lower life cycle costs, 50 percent less solids production, and smaller plant footprint, all establish the potential benefits of this new approach to wastewater treatment and reclamation using membrane filtration on primary wastewater effluent.

*Commercialization Potential*

This system could be applied to wastewater treatment for flow relief. By stressing the membranes and producing the same high water quality, the idea of recycling water and management of wastewater discharge combines into one project.

*Recommendations*

It is necessary to study how other configurations of MF units could treat primary effluent. It will also be important to create dialogue between the regulatory agencies to discuss possible alternatives for reuse and discharge.

### 2.4.2.5. Benefits to California

**A. Chlorine Tolerant Membranes**

As the population continues to increase in Southern California (and other areas in the California), water agencies will have to address the issue of increasing water demand. In Orange County, the population is estimated to increase to more than 3 million in the next 20 years. Reliable, safe and cost-effective sources of potable water must be developed to sustain population growth in Southern California. Developing non-traditional water sources for potable purposes require advanced water treatment facilities, which ultimately include membrane processes. The use of highly efficient, low fouling membranes would ultimately increase product water throughput while minimizing associated treatment costs.

TFC polyamide membranes operate at lower operating pressures than cellulose acetate membranes, which can translate into significant energy savings of 30% to 40%. Using a lower pressure TFC membrane that exhibits fouling resistance would further reduce energy costs as well. Less biofilm proliferation and accumulation on the membrane surface would result in lower operating pressures and subsequently lower energy costs. An increase in feed pressure of 25psi due to membrane biofouling is estimated to result in an increase of $7000 (500gpm, 75% pump efficiency) at $0.10/KWH (Dow Chemical, 1999). Minimizing the occurrence of membrane biofouling through the use lower fouling, more efficient TFC membranes could ultimately result in significant energy savings for the California water producer already faced with looming power concerns.

**B. Brine Disposal**

As mentioned in the introduction section, water recycling is foreseen as one of the best alternatives to meet the ever-increasing water demand. It is through recycled water that the depleted groundwaters are replenished, saline water intrusion from the ocean is prevented, and surface waters are augmented. California is one of the states that will suffer severely from polluted or depleted water resources in the near future. Currently, water demand in Southern California is being met by imported water from the northern region and from the Colorado River Project. This method of supply is highly expensive and not reliable from a long-term perspective. Therefore, the Orange County Water District, one of the leading research utilities in the US, is currently involved in extensive research on water recycling and groundwater replenishment.

The Fluidized Bed Biofilm Reactor with Granular Activated Carbon technology that has been introduced and discussed in this report has been proven to be very effective in the treatment of the RO brine concentrates. It is capable of removing nitrates completely sulfates partly from the brine waste streams. Furthermore, it is conceivable to upgrade the FBBR-GAC system to achieve sulfate reduction. One notable advantage of fluidized bed reactors is that they require minimal space, and the reactor size is relatively smaller as compared to conventional techniques due to excessive biomass growth. The reaction time is short and the treatment efficiency is high, making it easily adoptable by the utilities planning to employ the RO technology to recycle water, in residential areas where land availability is scarce or limited.

**C. IMANS™**

This research and demonstration testing could significantly alter the manner in which wastewater agencies discharge into the ocean or any other water body. By evaluating the microfiltration process as a means of disposing primary effluent, alternate methods can help better mange waste discharges.

## 2.5. Task 2.5 Disinfection Alternatives

### 2.5.1. MWD Study – Task 2.5 Disinfection Alternatives

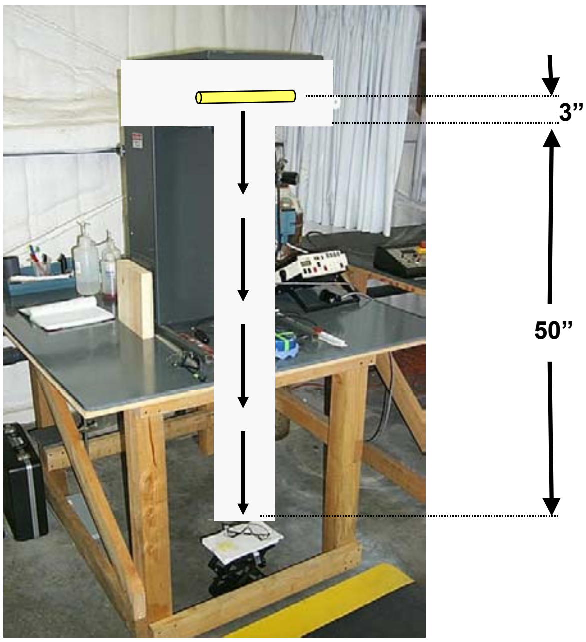
#### 2.5.1.1. Objectives

The objectives of this project task were as follows:

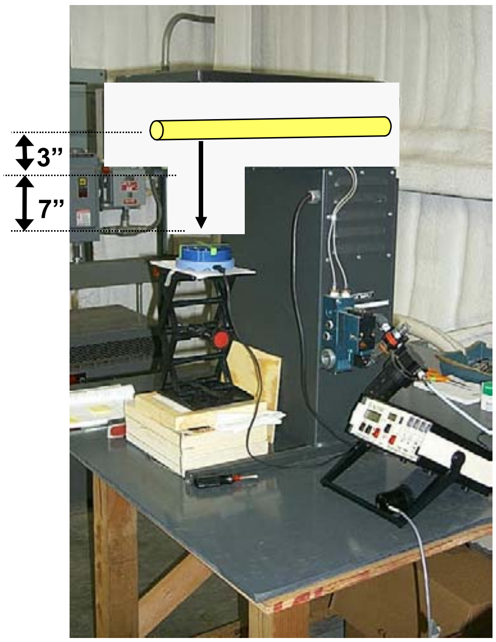
- Evaluate the ability of heterotrophic bacteria to repair and/or regrow following UV treatment;
- Compare disinfection effectiveness of pulsed UV and medium-pressure UV lamps against the single-stranded RNA virus MS-2 (which is a surrogate for human enteric viruses and polio);
- Evaluate the disinfection effectiveness of UV lamps against two organisms which may be a disinfection surrogate for *Cryptosporidium*, phi-6 (a double-stranded RNA virus) and Bacillus subtilis (a bacteria encapsulated in a spore structure with double-stranded DNA);
- Determine the ability of *Cryptosporidium parvum* to self-repair its infectivity after exposure to UV light; and,
- Determine the disinfection effectiveness of UV light against Giardia lamblia, another protozoan pathogen found in drinking water.

#### 2.5.1.2. Approach

The disinfection experiments for this project were conducted with low-pressure (for very low UV dosages required in G. lamblia tests), medium-pressure, and pulsed-UV lamps at the bench-scale (Figure 8 and Figure 9). Microorganisms exposed to UV light from the low- and medium-pressure UV lamps were done so with a collimated-beam unit (Calgon Carbon Corp., Pittsburgh, Penn.) (Figure 8).




(a) Medium-Pressure Lamp Configuration




(b) Low-Pressure Lamp Configuration

**Figure 8: Continuous-wave collimated beam**
**(two distances shown are the distance from the lamp to the collimating tube and the length of the collimating tube)**

The lamps are mounted 3 in. above 2.5-in. inside-diameter polyvinyl chloride (PVC) collimating tube with the interior of the tube painted flat black to minimize reflected light. A pneumatic shutter had opening/closing times of less than 0.5 sec. Collimated experiments exposed continuously stirred suspensions of microorganisms in 0.5-cm (0.2-in.) deep, 10-mL volumes contained in a 60-mm (2.4-in.), sterile, Permanox tissue-culture dish (Nalge Nunc International, Rochester, N.Y.). Exposure times were adjusted to keep the shutter interference time at less than five percent of the total exposure time. The collimating tube could length was either 10 in., 20 in., or 50 in. UV irradiance was measured by radiometer (model IL 1700, SED240 detector with W diffuser; International Light, Inc., Newburyport, Mass.) and a potassium-iodide actinometer described elsewhere.

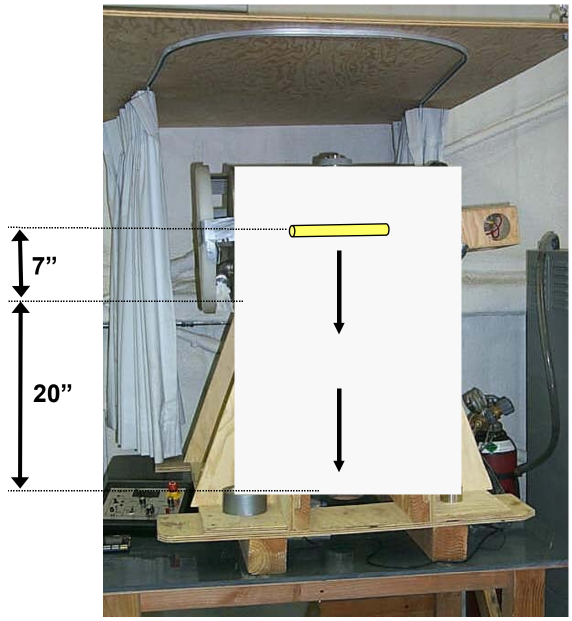



**Figure 9: Pulsed-UV collimated beam apparatus**

The dose of germicidal UV light transferred to the microorganisms was calculated after measuring the UV light beam’s center irradiance value before and after exposing each sample. This center value was then pro-rated for locations away from the center according to an irradiance distribution determined at the beginning of the study. To determine this variation in intensity across the water surface, UV irradiance was measured once at the beginning of the study across a 0.5-cm (0.2-in.) planar grid at 25 locations. Averaged radiometer readings were adjusted by absorbance of the natural water matrix according to the governing principles of the Beer-Lambert. UV irradiance was then multiplied by the exposure time to determine a dose of germicidal UV light, measured in mJ/cm2. UV dose for the pulsed-UV experiments was measured by the potassium-iodide actinometer. A correlation between radiometer-measured dose and actinometer-measured dose was made so that results from the low- and medium-pressure UV lamps could be compared to the pulsed-UV lamp.

A standard repair/regrowth protocol calls for samples to be irradiated and placed in a controlled environment for a specific time. This study called for the potential of heterotrophic bacteria to re-grow and repair after UV irradiation to be evaluated in both a lighted and dark environment. Water samples exposed to UV light were taken from a 6 gpm pilot plant operating in the ozone/biofiltration mode. Aliquots of irradiated samples were placed in sterile petri dishes in the following controlled laboratory environments. To determine the contribution of bacterial repair compared to regrowth potential, aliquots of heterotrophes were inoculated into filter-sterilized natural water and incubated to establish baseline heterotrophic regrowth potential. A daylight environment was simulated by exposure to two 15 W daylight simulator lamps suspended above the samples. These lamps provided non-ionizing visible radiation to simulate water storage in an open-air reservoir after treatment. Samples were also incubated in petri dishes in a dark cabinet to simulate the distribution system. The temperature of both samples remained at ambient conditions.

<u>*Experiments were conducted in the following test matrix:*</u>

Heterotrophic bacteria inactivation after contact with chlorine and chloramines; Heterotrophic bacteria inactivation after exposure to pulsed-UV light; and Heterotrophic bacteria inactivation after exposure to pulsed-UV light and addition of chloramines (up to seven days storage in a simulated distribution system);

- Proliferation of heterotrophic bacteria after exposure to pulsed-UV light and placement in both a simulated open-air reservoir and simulated distribution system (up to 7 days storage)
- Baseline heterotrophic regrowth potential in bacteria-inoculated, filter-sterilized water placed in both simulated environments (up to 7 days storage).
- Incubation environments were temperature controlled (to 20 °C) and aliquots of sample were taken from the petri dishes at 3 and 7 days (72 and 168 hours).
- Test procedures were conducted in a controlled and repeatable manner for each test. A detailed discussion of all of the test procedures can be found in the Appendix under the Task 2.5 report

**Materials and Methods**

<u>*Alkalinity*</u>

Alkalinity was determined by titration, as described in *Standard Methods* (APHA 1998).

<u>*Bacillus Subtilis*</u>

*B. subtilis* were grown on trypan blue agar plates for 2 to 3 days at 37 °C and then incubated at room temperature for 3 to 4 days to form spores from nutrient exhaustion. Organisms were removed from plates, re-suspended in sterile phosphate-buffered water, and heated at 82 °C for 15 minutes, and then immediately stored at 4 °C until ready for UV exposure. A detailed discussion of the dilution and quantification of the bacteria counts can be found also in Task 2.5 report the Materials and Methods section in the appendix.

<u>*Cryptosporidium Parvum*</u>

*C. parvum* oocysts were obtained from the University of Arizona. Once harvested from the infected calves, the oocysts were cleaned by sequential centrifugation through sucrose and cesium chloride and placed in an antibiotic solution containing 0.01 percent polyoxyethylenesorbitan monolaurate to prevent clumping. Preparation of the oocysts, purification, concentration, inoculation, and counting procedures have been documented and are presented in the Task 2.5 report the Materials and Methods section in the appendix.

<u>*Giardia Lamblia*</u>

*Giardia* cysts (WB strain) were obtained from the University of Calgary as trophozoites in culture. The WB strain cysts for these experiments were passed three times through gerbils before use. Gerbils were provided with food and water as needed and dexamethasone (30 mg/mL) was added to their drinking water to enhance cyst production. Preparation, transfer, and subsequent inoculation and counting procedures have been documented and are presented also in the Task 2.5 report under the Materials and Methods section in the appendix.

*Hardness*

Hardness (total) was measured with EDTA titration to define the sum of calcium and magnesium concentrations, and expressed as calcium carbonate (mg/L) as described in *Standard Methods* (APHA 1998).

*Heterotrophic Bacteria*

Heterotrophic bacteria were analyzed using membrane filtration and incubation on R2A media at 28 $^{o}$C for 7 days, according to *Standard Methods* (APHA 1998). Plating was conducted in triplicate, and results are presented as cfu/mL.

*Most Probable Number Determination*

The Most Probable Number (MPN) technique uses statistical analysis to provide a modal value of organism density based on probability theory. The Hurley and Roscoe-based MPN calculator was used to calculate MPN values for the dilution series used in this study.

*MS-2 Coliphage*

MS-2 coliphage was obtained from American Type Culture Collection with *Escherichia coli* Famp as the bacterial host. The assay was conducted according to the procedure described in the Information Collection Rule (USEPA 1996a, USEPA 1996b), along with an added purification stage. MS-2 was grown onto tryptone agar plates, and resuspended into a saline-calcium buffer solution. MS-2 Coliphage assaying, purification, dilution, transfer, and experimental procedures are presented in the Task 2.5 report under the Materials and Methods section in the appendix.

*pH*

Water pH was analyzed by a pH meter with Accuracy of ±0.02 pH units (model 920A; Orion Research, Inc., Boston, Mass.)

*Phi-6 Bacteriophage*

Phi-6 bacteriophage was assayed similarly to MS-2 coliphage (a plaque assay). The host was grown in nutrient broth yeast extract (NBY) media and optimum plaquing was observed when the host was grown for two consecutive 24 hr periods at 28 $^{o}$C with agitation at 120 rpm prior to infecting with phi-6 phage. Plaque assay was performed by the top agar method in NBY media supplemented with 1 percent agar and incubated overnight at room temperature.

*Temperature*

Temperature was measured using a thermometer calibrated against a certified thermometer by the National Bureau of Standards.

*Turbidity*

Turbidity was measured with a Hach 2100N Turbidimeter calibrated with dilute formazin solutions as specified by the manufacturer with an accuracy of ±2 percent.

*UV Light Absorbance at 254 nm*

UV light absorbance at 254 nm in a 1-cm quartz cuvette was measured by a spectrophotometer (Lambda 3B, Perkin Elmer Corp., Wellesley, Mass.), and is reported in units of $cm^{-1}$.

#### 2.5.1.3. Outcomes

- The ability of UV light to disinfect bacteria, viruses, and protozoa suspended in a filtered drinking water was evaluated in this study. The immediate effects of 20 $mJ/cm^2$ of UV light against heterotrophic bacteria was equivalent to traditional chemical disinfectants chlorine (1 minute contact) and chloramines (61 minutes contact), each providing more than 3.5 $log_{10}$ inactivation of bacteria.
- UV disinfection alone was investigated for its ability to provide disinfection of *B. subtilis* aerobic spores, MS-2 coliphage (a single-stranded RNA virus surrogate), and phi-6 bacteriophage (a double-stranded RNA virus surrogate). UV also seen to be effective in disinfecting these three organisms, with a dose of 40 $mJ/cm^2$ providing 1.9, 1.5, and 2.0 $log_{10}$ inactivation, respectively.
- UV alone was also investigated for its ability to provide disinfection of *G. lamblia* cysts in water (results quantified with an animal infectivity assay), and study results found that a very low UV dose of 1.4 $mJ/cm^2$ would provide a 2 $log_{10}$ inactivation of *G. lamblia*.
- UV disinfection experiments were conducted with another protozoan parasite, *C. parvum*, to determine if the low UV dosages used in disinfection may allow these organisms to repair themselves and become re-infective (at dosages up to 17 $mJ/cm^2$). However, within the amount of variability inherent in the *C. parvum* experiments conducted, it could not be concluded whether or not repair mechanisms exist which can overcome UV disinfection.
- Experiments were conducted to determine if the innovative pulsed-UV lamp design could enhance the disinfection achieved compared with the more conventional lamp type by investigating the two lamps' ability to inactivate heterotrophic bacteria, *B. subtilis*, MS-2, phi-6, and *C. parvum*. Across all the experiments, there were no significant difference in the results obtained with one lamp or the other.
- This study also evaluated the effects of UV only, compared with the effects of UV followed by addition of chloramines, on the biological stability of treated samples (characterized by the regrowth and/or repair of heterotrophic bacteria after treatment). When samples were treated with UV dosages up to 60 $mJ/cm^2$, bacteria were reduced to levels of less than 10 CFU/mL. However, after incubation on post-irradiated water, bacteria reestablished pretreatment levels within a 3-day period. When samples were treated with 20 $mJ/cm^2$ UV dose followed by a dose of 2.6 mg/L chloramine, the samples remained biologically

stable for at least 7 days. Samples treated by UV/chloramines kept heterotrophic bacteria levels below 5 CFU/mL.

#### 2.5.1.4. Conclusions and Recommendations

**Conclusions**

Table 4 summarizes the UV disinfection results for the organisms evaluated in this study. This also study demonstrated that equivalent disinfection of each organism tested could be achieved no matter what lamp type was evaluated. Figure 10 demonstrates that both the medium-pressure and pulsed-UV lamps provided similar disinfection when compared on an equivalent UV dose measurement basis.

Table 4: UV Dose Required to Provide 2-$\log_{10}$ Inactivation of Target Organism

| Organism Type | UV Dose ($mJ/cm^2$) |
|---|---|
| **Giardia lamblia** | *<2* |
| **Cryptosporidium parvum** | *<12* |
| **Heterotrophic Bacteria** | <20 |
| **Phi-6 bacteriophage** | 40 |
| ***Bacillus subtilis*** | 42 |
| **MS-2 coliphage** | 53 |

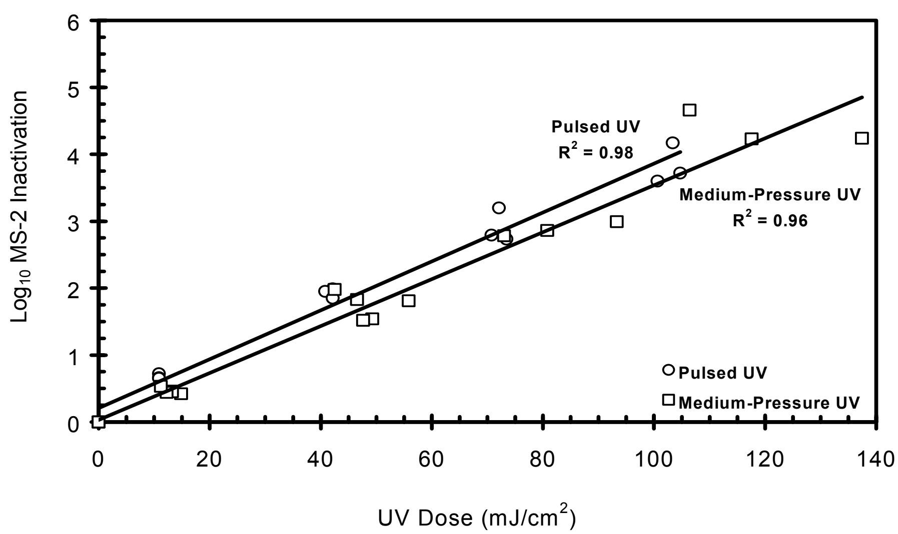



**Figure 10: Effect of Medium-Pressure and Pulsed-UV light on MS-2 Coliphage**

- The most susceptible organisms to UV light were protozoa and heterotrophic bacteria, with UV dosages of less than 20 $mJ/cm^2$ providing 2 $\log_{10}$ inactivation.
- Organisms more resistant to UV light were the double-stranded RNA virus phi-6, followed by *B. subtilis* and then the single stranded RNA virus MS-2. For these organisms, a UV dose between 40 and 53 $mJ/cm^2$ was required to provide 2 $\log_{10}$ inactivation.
- The disinfection provided by UV on the human pathogen *G. lamblia* was even more effective than what has been previously reported for *G. muris* (Craik et al. 2000), a more easily handled rodent parasite.
- This task study shows that the process of using UV light to control post-filtration heterotrophic bacteria would need to be followed by a residual disinfectant such as chlorine or chloramines to provide a water with biological stability.
- This study demonstrated that similar disinfection of many of organisms could be achieved by either a more traditional medium-pressure, continuous-wave UV lamp or an innovative pulsed-UV lamp type. The disinfection provided by both lamps was similar when compared on an equivalent UV dose basis. Both lamps were effective in the treatment of *C. parvum*, but it could not be determined whether or not *C. parvum* could repair itself following UV treatment.

**Commercialization Potential**

- The research conducted in this report was done at the bench-scale, but showed that UV light from either low-pressure, medium-pressure, or pulsed-UV can effectively inactivate bacteria, protozoa, and viruses suspended in a filtered drinking water. Although no energy comparisons were made, it is expected that energy use would be highest for pulsed , then medium-pressure, and least for low- pressure UV lamps. The UV process is a technology currently made available for wastewater disinfection by a number of manufacturers, although it is a new process for the treatment of drinking waters. Pending future research into the ability of the process to scale-up from the bench-top to large-scale UV reactors (treating several million gallons of water per day), the process needs additional research before large-scale implementation and commercialization.

**Recommendations**

- Future studies should be conducted to determine if *C. parvum* repair mechanisms may exist after UV treatment. Because of the similar disinfection achieved with different UV lamp types, these future studies could be limited to one lamp type (such as the low-pressure UV lamp used in the *G. lamblia* studies reported here).
- To better quantify effects of organism repair in future studies, it would be beneficial to wait until improvements in *C. parvum* infectivity assays are made so that variability is reduced.
- Future research must complement the bench-scale data presented here and elsewhere by evaluating the process efficiency and hydraulic characteristics of large-scale UV reactors. These evaluations should make recommendations for monitoring of transferred UV dosage and reporting of continuous disinfection

effectiveness (i.e., on-line UV dosage measurement) so that drinking water treatment requirements can be met.

#### 2.5.1.5. Benefits to California

UV disinfection is fast becoming a great benefit to California water treatment utilities. However, the recommendations stated above should be followed before implementing large-scale UV technology. Although the process shows to be viable at the bench-scale, large-scale technology with on-line monitoring capability are still in development and should be evaluated before implementing the technology as a reliable barrier to waterborne human disease and illness.

### *2.5.2.* OCWD Study -- Task 2.5 Disinfection Alternatives

The focus of this research was ultraviolet disinfection. UV irradiation is a technology that has proven to be effective for disinfection of various water sources. The advantages to the use of UV disinfection are numerous. Among the advantages are: no chemicals are used, eliminates the need for storing hazardous chemicals such as gaseous chlorine, potentially harmful disinfection byproducts are not formed, cost effective when compared to chemical-based alternatives, requires minimum operator attention and labor. This research focused on the use of a low pressure-high intensity, open channel UV system, collimated beam apparatus, and a pulsed UV system for inactivation of various microorganisms.

#### 2.5.2.1. Objectives

The objectives of this research were:

- Evaluate the low-pressure high-intensity open channel UV system known as the TAK 55, manufactured by Wedeco-Ideal Horizons, using the "Proposed UV Disinfection Testing Protocol to Demonstrate Compliance with the California Reclamation Criteria" in order to meet Title 22 standards.
- Determine the efficiency of UV disinfection for inactivation of protozoa.
- Establish dose curve for pulsed UV and compare the performance of pulsed UV for disinfection of microorganisms using various water matrices.

#### 2.5.2.2. Project Approach

Figure 11 shows a schematic diagram of the pilot facilities.

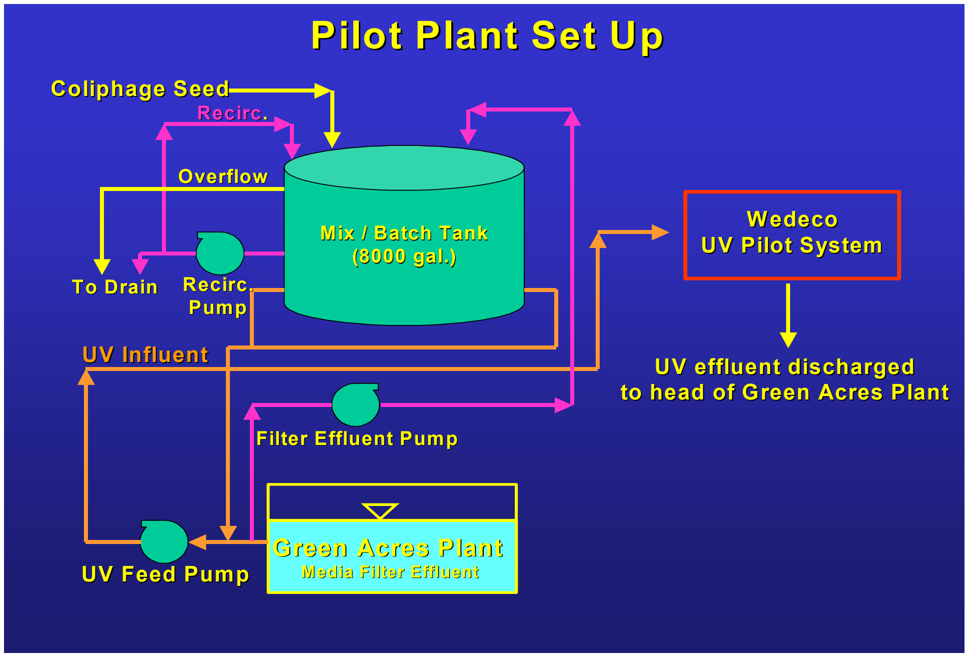



**Figure 11: Schematic Diagram of *Wedeco-Ideal Horizons TAK 55 Pilot System***

<u>*Evaluation of Wedeco-Ideal Horizons TAK 55 System*</u>

The Wedeco-Ideal Horizons TAK 55 low pressure-high intensity UV system was set up at the OCWD Green Acres Project (GAP) facility which is an eight million gallon per day tertiary treatment plant with flocculation and dual media filtration followed by chlorination for non-potable reuse. The TAK 55 system was set up to receive water after the dual media filtration process just upstream of the chlorination process. This set up enabled the comparison of the effectiveness of the UV disinfection process with an approved chlorination process. The system was run continuously for four weeks and the effluent was sampled at various times for total coliform concentrations. Following this testing, the system was fed with 6000 to 8000 gallon batches of water seeded with coliphage MS2 virus indicator organisms. Several batch tests were run in which influent and effluent samples at various irradiation doses were taken. In addition, all doses run on the TAK 55 system were also run on a collimated beam apparatus in the laboratory for comparison.

<u>*Efficiency of UV for Protozoa Inactivation*</u>

Three different collimated beam apparatus were used to evaluate the effectiveness of UV for inactivation of Giardia muris (G. muris) and Bacillus subtillus (B. subtillus). The three collimated beam apparatus used were a low pressure, low intensity; low pressure, high intensity and pulsed. Both G. muris and B. subtillus were irradiated at various doses using various water qualities. The irradiated samples were sent to an outside laboratory, Biovir Laboratories, for analysis using mouse infectivity assays.

*Evaluation of Pulsed UV*

A pulsed UV system from Innovatech was evaluated for the disinfection of various microorganisms using various water qualities. The pulsed UV system used consisted of an eight inch diameter vessel r that contained a single lamp located parallel to the flow of water. The pulsed UV chamber was first set up to receive secondary effluent as the feed water source. This UV system was designed for use on drinking water but had never been evaluated for use on wastewater. The system was run continuously and sampled on occasion for total coliform concentrations. In parallel to the eight inch treatment vessel was run a bench scale flow through test chamber. This test chamber serves the same function as a collimated beam apparatus for conventional UV systems. The test chamber allows for various doses of UV to be tested on a bench-scale basis using small batches of water. Other water sources including deionized and reverse osmosis effluent water were run through the treatment chamber. In addition the test chamber was run using various water seeded with coliphage MS2 virus indicator organisms.

#### 2.5.2.3. Project Outcomes

*Evaluation of Wedeco-Ideal Horizons TAK 55 System*

The TAK 55 system was found to be most effective when used with three banks in series. This system worked best when the flow rate was limited to 17 gpm / lamp to achieve a four log reduction in coliphage MS2 on water with a transmittance of 55 % or less. The system proved to be successful in meeting the criteria established by State of California Title 22 Wastewater Reclamation Criteria.

*Efficiency of UV for Protozoa Inactivation*

The use of collimated beam apparatus proved that UV is effective for inactivation of protozoa species including Giardia muris and Bacillus subtillus. A four log reduction of G. muris was achieved on all three collimated beam apparatus evaluated at a dose of 5 mWsec / square cm. A four log reduction of B. subtillus was achieved on all three collimated beam apparatus evaluated at a dose of 80 mWsec / square cm. It was found that the low pressure, high intensity collimated beam apparatus was most efficient but that all three systems were equally effective.

*Evaluation of Pulsed UV*

The addition of a baffle system to the pulsed UV eight inch diameter treatment vessel proved to be key to the system's effectiveness. This baffle allowed for better flow through characteristics ensuring that all of the water to be treated would come in close contact with the pulsed UV lamp. A four log reduction in total coliform on secondary effluent was achieved at a UV dose of 80 mWsec / square cm. The theoretical dose calculated using the test chamber was compared with the doses used on the eight inch diameter treatment vessel. The correlation factor between the two systems was found to be 0.9 or 90% for the inactivation of total coliform in secondary effluent.

### 2.5.2.4. Conclusions and Recommendations

**Conclusions**

*Evaluation of Wedeco-Ideal Horizons TAK 55 System*

- The TAK 55 technology is capable of achieving 4-log MS2 inactivation.
- The pilot plant performance improved when the number of banks online was increased from 2 to 3 banks.
- The MS2 inactivation results tracked the lamp power set. At low power set, the flow per lamp was approximately 70 percent of the high power set.
- The maximum flow per lamp for achieving 4-log inactivation of MS2 was 12 gpm/lamp at low power set and 17.2 gpm/lamp at high power set for the filtered effluent, with a UV transmittance of less than 55 percent and turbidity greater than 1 NTU.

*Efficiency of UV for Protozoa Inactivation*

- 4-log inactivation of B. *subtilus* spores was achieved at a dose of about 80 $mWs/cm^2$
- 4-log inactivation of G. *muris* was achieved at a dose of about 5 $mWs/cm^2$
- G. *muris* is extremely susceptible to sticking which can cause inconclusive results when not tested in a very controlled environment

*Evaluation of Pulsed UV*

- The Innovatech Pulsed UV chamber in its present configuration was designed for relatively clear drinking water. The pulsed UV testing on the OCWD secondary effluent source provided an excellent opportunity to investigate the effectiveness of the current chamber design on waters with low UV transmissivity and high NTU levels. By introducing a baffle design to reduce the effective cross section and improve mixing within the chamber, it was possible to adapt this drinking water design to effectively treat the secondary effluent to the desired four log reduction, for a very reasonable dose level of 80 $mWs/cm^2$.
- Although the primary objective of testing the Innovatech Pulsed UV system at the Orange County test facility was to determine its applicability for treating the waste water, after the filtration and RO steps, and just prior to ground water re-injection, the Phase I tests on the secondary effluent provided an excellent opportunity to learn more about the system and introduce improvements.
- The testing using the special test chamber for flowing water testing showed that the use of pulsed UV for coliphage MS2 removal in tertiary effluent was not as effective as continuous-wave UV.

**Recommendations**

*Evaluation of Wedeco-Ideal Horizons TAK 55 System*

- The testing of the Wedeco-Ideal Horizons TAK 55 lamp technology has proven that this technology is viable for meeting the disinfections standards set by the

California Title 22 guidelines for wastewater reclamation. It is recommended that this system be considered for use in future or current municipal reclamation projects. For current installations this system can replace or enhance disinfection systems currently in place. Many applications currently use chemical disinfection with chlorine as the primary disinfectant.

*Efficiency of UV for Protozoa Inactivation*

- Tests need to be run using G. muris as an indicator organism for evaluation on a pilot scale UV system without having to lower the transmittance to an unreasonable level. It is also necessary to find a way to keep the G. muris from sticking to the plastic batch tank and the plastic PVC pipes which are connected at the influent and effluent ends of the pilot UV units.

*Evaluation of Pulsed UV*

- The next step that should occur would be to test the pulsed UV 8″ diameter pilot unit on membrane treated wastewater. The pulsed UV technology seems better fitted toward cleaner water sources. Several wastewater reclamation projects use membrane processes upstream of UV to improve the effectiveness of the pulsed UV system.

### 2.5.2.5. Benefits to California

- The testing done as part of this study could lead to certification of the Wedeco-Ideal Horizons TAK 55 technology by the California Department of Health Services for use in Title 22 reclamation applications. The certification of this technology would lead to an increase in options for agencies in need of disinfection technologies for reclamation projects.
- This task shows that low levels of UV radiation are effective in disinfecting harmful protozoa. This allows other agencies to use UV technology in place of conventional disinfection technologies, which may be more expensive or may create unwanted disinfection byproducts
- There is now evidence to show that pulsed UV technology can be applicable to disinfection for reclamation applications.

## 2.6. Task 2.6 Investigate Solids Processing Techniques

### 2.6.1. Objectives

- Evaluate the economics of using the BIOFREEZE™ unit for conditioning water treatment plant residuals.
- Determine if biological wastewater residuals can obtain the same separation rate as inorganic water treatment plant residuals.
- Evaluate the economics of using BIOFREEZE™ for conditioning wastewater residuals.
- Evaluate freeze concentration of reverse osmosis brine to determine if separation of salts can be achieved.

### 2.6.2. Approach

A pilot-scale demonstrator unit was constructed for this project. This unit was a batch freezer with two compartments that could simultaneously freeze and thaw. This approach allowed the demonstrator to maximize energy efficiency by recovering energy. By recirculating the water in a channel during the freezing process (called *dynamic freezing*), this refrigeration system is used to freeze a concentrated brine solution.

### 2.6.3. Outcomes

**Materials Tested**

The purpose of this study was to evaluate the effects of freeze-thaw technology on water and wastewater residuals. All testing took place at OCWD in Fountain Valley, CA, on specific residuals of the following types:

- Alum sludge from a water treatment plant.
- Ferric sludge from a water treatment plant.
- Thickened activated biological sludge (TWAS) from a wastewater treatment plant.
- Brine from microfilter (MF) and RO plants using a relatively new technology, FC.

**1) Alum Sludge**

Pilot testing of alum sludge (Table 5) was conducted with sludge produced at the Metropolitan Water District (MWD) in La Verne, California, which treats an average daily flow of 150 mgd. Alum is the primary flocculant aid used at the plant with an average dose of 4 mg/L. Presently, the thickened sludge is discharged to the industrial sewer leading to the sanitation district for treatment.

<u>*Volume Reduction*</u>

The F/T conditioning did reduce sludge volume. The volume reduction was calculated by subtracting the volume of the sludge after F/T conditioning from the volume of sludge before F/T conditioning, then dividing that value by the volume of sludge before F/T conditioning. The sludge volume of the freeze/thaw conditioned sample after gravity thickening ranged from

74 to 94 percent, with an average of 84 percent. These values compared favorably to volume reduction results previously obtained by EPRI, which ranged from 63 to 91 percent.

*Supernatant Quality*

The solids concentration of the supernatant, collected after gravity thickening for 2 hours, ranged from 650 to 930 mg/L. These values appear to be much higher than the results previously reported by EPRI that ranged from 100 to 375 mg/L. Supernatant quality probably was impacted by the rate at which the sludge was frozen.

*Gravity-Thickened Solids Concentration*

The solids content of the gravity-thickened sludge ranged from 11 to 12.5 percent. These results were similar to those experienced in previous EPRI studies, which ranged from 6 to 23 percent, with an average value of 12 percent.

*Dewatering Using a Belt Filter Press*

The solids concentration of gravity thickened solids dewatered on a pilot-scale belt filter press, ranged from 22.3 to 26 percent. These results are very similar to those previously obtained by EPRI, which ranged from 18 to 22.5 percent.

**Table 5: Freeze/Thaw Testing Results for Alum Sludge**

| Test Run | 1 | 2 | 3 |
|---|---|---|---|
| **Influent Concentration (% Solids)** | 0.7 | 2 | 3.3 |
| **Volume of Sample (gal)** | 10.4 | 12.7 | 10.4 |
| **Freezing Time (min)** | 150 | 195 | 180 |
| **Final Temperature ($^{o}$F)** | 32 | 2 | 22 |
| **Volume Reduction** | | | |
| ***After Belt Filter Press (%)*** | 97 | 91 | 87 |
| **Supernatant Quality (mg/L)** | 650 | 750 | 930 |
| **Gravity Thickened (% Solids)** | 11.1 | 11.4 | 12.5 |
| **Belt Filter Press (% Solids)** | 26 | 22.3 | 24.4 |

**2) Ferric Chloride Sludge**

Pilot testing of sludge conditioned with ferric chloride (Table 6) was conducted using sludge from MWD water treatment facility. The sludge is the product of a process that treats an average daily flow of three mgd, using ferric chloride at an average dose of 6 mg/L. The average solids concentration of the sludge after thickening was approximately five percent. Presently, the thickened sludge is discharged to the industrial sewer leading to the sanitation district for treatment.

*Volume Reduction*

The F/T conditioning did reduce residuals volume. The residuals volume of the freeze/thaw conditioned sample after gravity thickening was reduced by 45 to 81 percent. The range of values is due the variance in the influent solids concentration and the freezing temperature.

*Supernatant Quality*

The solids concentration of the supernatant, collected after gravity thickening, ranged from 930 to 1,070 mg/L.

*Gravity-Thickened Solids Concentration*

The solids concentration of the gravity-thickened sludge had a percent solids range of 10 to 16 percent.

*Dewatering Using Belt Press*

The solids concentration of sludge dewatered on a belt filter press ranged from 22 to 32 percent.

**Table 6: Freeze/Thaw Testing Results for Ferric Chloride Sludge**

| Test Run | 1 | 2 | 3 |
|---|---|---|---|
| **Influent Concentration (% Solids)** | 2.4 | 5.7 | 6.2 |
| **Volume of Sample (gal)** | 12.5 | 8.3 | 9.6 |
| **Freezing Time (min)** | 240 | 165 | 180 |
| **Final Temperature (°F)** | 0 | 27 | -11 |
| **Volume Reduction** | | | |
| ***After Belt Filter Press (%)*** | 93 | 74 | 79 |
| **Supernatant Quality (mg/L)** | 1,070 | 930 | 970 |
| **Gravity Thickened (% Solids)** | 12.1 | 10.3 | 15.9 |
| **Belt Filter Press (% Solids)** | 31.8 | 22.3 | 29.2 |

### 3) Biological Sludge

The biological sludge was F/T pilot tested using TWAS from the Orange County Sanitation District (OCSD) Plant No. 2 in Huntington Beach, CA that treats an average daily flow of 150 mgd. The DAF-thickened TWAS had a solids concentration of approximately 8 percent. Presently, the TWAS undergoes anaerobic digestion and chemical addition for dewatering, before it is disposed of off-site by agricultural land application.

Unlike the inorganic sludges, the sludges subjected to F/T conditioning in this study were not reduced in volume. However, previous testing performed by OCSD resulted in volume reduction. In addition, when the F/T conditioned sludge was digested in OCSD pilot anaerobic digesters, the volume of methane per unit of feed increased by approximately 20 percent.

The results of this study (Table 7) were compared with the results reported by OCSD to determine the reasons for the large differences between the two sets of results. One major difference was that the freezing rate of the F/T demonstrator was unable to be controlled; therefore the freezing rate used in this study was more rapid than the rate of freezing in the OCSD study. Another possibility was that the TWAS sample needed to remain frozen for a length of time (referred to as curing time) to improve its dewatering and gas production characteristics. Based on the OCSD study results, it is recommended that further testing be performed on TWAS while adjusting the freezing rate and curing time.

**Table 7: Biological Sludge Freeze/Thaw Results**

| Test Run | 1 | 2 | 3 |
|---|---|---|---|
| **Influent Solids (% Solids)** | 3.4 | 3.4 | 3.44 |
| **Volume of Sample (gal)** | 13.75 | 10 | 10 |
| **Freezing Time (min)** | 170 | 180 | 165 |
| **Final Temperature ($^{o}$F)** | -13 | 28 | 11.6 |
| **Supernatant Quality (% Solids)** | 2.79 | 3.24 | 3.37 |
| **Gravity Thickened Solids (% Solids)** | 3.23 | 3.44 | 3.43 |

### 4) Brine

The freeze concentration (FC) pilot testing (Table 8) was performed at the OCWD Water Factory 21 in Fountain Valley, CA, using brine solution from their MF research project which had a TDS concentration of approximately 5000 mg/L.

*Product Ice Quality*

The FC process produced ice with TDS concentrations which ranged between 2757 and 5100 mg/L, and averaged approximately 3800 mg/L. The parameters which varied for the FC testing were the recirculation rate and the freezing time. The recirculation rate proved to have some effect (especially when compared with the test run that included no recirculation) while the freezing time proved to have a considerable effect, with slower freezes resulting in TDS removal in the product ice.

*Volume Reduction*

For the FC test runs, the influent brine volume was reduced between 24 and 89.6 percent.

**Table 8: Brine Freeze Concentration Results**

| Test Runs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Influent Brine TDS (mg/L)** | 5,290 | 5,290 | 5,374 | 5,260 | 5,330 | 6,580 |
| **Volume of Sample (gal)** | 15.8 | 14.2 | 6.7 | 6.7 | 15.6 | 5 |
| **Freezing Time (min)** | 173 | 205 | 175 | 58 | 88 | 39 |
| **Final Brine Temperature ($^{o}$F)** | 36 | 35 | 36 | 2 | 35 | 36 |
| **Recirculation Rate (gpm)** | 4 | 4 | 5.6 | 0 | 6.3 | 7.0 |
| **Surface Velocity (ft/min)** | 3.8 | 3.8 | 6 | 0 | NR | NR |
| **Volume of Brine (gal)** | 4.2 | 5 | NR | 0.7 | 5.6 | 3.8 |
| **Volume of Ice (gal)** | 11.6 | 9.2 | NR | 6 | 10 | 1.2 |
| **Volume Reduction in Brine for disposal (%)** | 73.4 | 64.8 | NR | 89.6 | 64.1 | 24 |
| **TDS Concentration of Effluent Brine (mg/L)** | 9,984 | 8,823 | 6,690 | 5,625 | 7,530 | 10,260 |
| **TDS Concentration of Ice (mg/L)** | 3,813 | 2,757 | 600 | 5,100 | 3,580 | 3,720 |

NR – Not Recorded

**Power Requirements**

A power meter was installed to measure the power use of the refrigeration compressor (Table 9). Of the total of 15 trials run, seven were monitored for power consumption. Power consumption for these test runs ranged between 3.3 and 15.1 kWh. This variance is attributed to the varying volumes of sludge used in the test unit.

A more accurate measure of power efficiency is the power consumption per ton of product frozen. This measurement varied between 118.7 and 393.6 kWh per ton. Since during the first five trials the test unit was not insulated, these trials do not reflect its true power efficiency. During the last two trials, the unit was insulated, and comparison of the average of the last two with the average of the first five trials showed the insulated unit to be operating 2.6 times as efficiently as the unit without insulation.

However, even the average of 124 kWh/ton of frozen product probably does not reflect the efficiency an actual BIOFREEZE™ unit. The inefficiencies of the demonstration unit's small scale have a large effect on the power consumption. Based on SIR experience, the power consumption should range between 24 and 40 kWh/ton. A full-scale demonstration needs to be examined to confirm their power consumption estimate.

**Table 9: Power Consumption**

| Test Run | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| **Length of Freeze (min)** | 164 | 164 | 179 | 173 | 205 | 58 | 88 |
| **Energy Used (kWh)** | 11.8 | 12.6 | 12.3 | 11.7 | 15.1 | 3.3 | 5.4 |
| **Volume of Ice (gal)** | 10.4 | 7.9 | 9.2 | 11.7 | 9.2 | 6.7 | 10 |
| **Estimated Energy Used (kWh/ton)** | 270.3 | 381.4 | 321.7 | 239.8 | 393.6 | 118.7 | 129.5 |

* - Unit was insulated

### 2.6.4. Conclusions and Recommendations

#### 2.6.4.1. Conclusions

At the end of the study period, 15 test runs have been completed using the demonstrator unit and the following information have been reported:

- Mechanical F/T is extremely effective at reducing inorganic residual volumes, achieving up to a 94% reduction.
- Mechanical F/T of the wastewater biological residuals collected for this study did not produce the high level of separation achieved with the inorganic sludges.

- FC of RO brine did produce a concentrating effect, and reduce the volume of concentrated brine for disposal. Results of the testing did not appear to achieve low concentrations of TDS in the ice (average ice TDS, 3260 mg/L; expected ice TDS, 500 mg/L).
- Most of the power data collected during this study was inaccurate due to the BIOFREEZE™ unit not being insulated. The two trials that were conducted with the demonstrator insulated resulted in power consumption of 118.7 and 129.5 kWh/ton of frozen residual, which is very similar to data observed by EPRI.
- The economic analysis of the freeze/thaw method appeared to be cost competitive with conventional treatment of water residuals.

#### 2.6.4.2. Commercialization Potential

**Capital Investment**

Preliminary engineering of residuals F/T plants dictates that the complete systems can be broken down into relatively standard and sometimes modular components. The plant systems proposed herein are basically divided into the following subsections:

- Raw Residuals Thickening
- Residuals Feed Handling and Filling Systems
- Residuals Freezing and Refrigeration Systems
- Product Ice Handling Systems
- Product Ice Melting, Heat Recovery, and Primary Separation Systems
- Final Residuals Product Separation
- For FC plants, all of the subsections are the same except for the subsection on raw residuals thickening, which is elimінated.
- Residuals Freeze/Thaw Freezing Load

The F/T process design and costing parameters are based on the quantity of residuals that must be frozen in each freezer during each freezing cycle. Formal industrial refrigeration design and evaluation of this type is based on tons of ice (2,000 pounds per ton) which must be produced during each 24-hour cycle. Residuals are usually characterized in plant operations in terms of gallons at a particular level of total solids (expressed as percentage). Since the freezing process is driven by the quantity of ice (by weight) to be produced, plant sizing is based on residuals volume as if it were water to be frozen. Actual liquid residuals are heavier than water because of their solids content. However, the weight of a comparable volume of water is used as the design standard.

<u>*Plant Cost*</u>

The total installed cost of a residuals plant is a direct function of the amount of ice produced each day. These costs are based on the use of modular equipment for vertical plate block freezers (11 tons of ice per day) on a repetitive cycle of approximately seven 1.6 ton batches per day. The BIOFREEZE™ costs are for individually customized refrigeration systems that would fit on a 40 foot truck bed. Adjusting the number of freezing plates in the freezer can accommodate intermediate freezer sizes. Refrigeration systems use ammonia as the refrigerant for the block freezers; ammonia or ammonia-equivalent is the refrigerant for the BIOFREEZE™.

*F/T Thickening Technology and Costs*

The economic advantages of freeze/thaw conditioning for water plant residuals are most attractive at slightly elevated concentrations of feed solids. Most water treatment residuals are generated at a solids concentration of 1 percent or less and are thickened to 2 or 3 percent solids by a simple gravity thickening. While feed materials of approximately 3 percent concentration respond very well to freeze/thaw conditioning, the economic advantage of the process is affected by the large volumes of water to be frozen. Consequently, thickening of feed streams with 3 percent or lower solids content to between 6 and 9 percent solids offers distinct economic advantages.

Relatively simple thickening technology with or without moderate doses of polymer or other coagulant aids can efficiently and economically raise feed concentrations to the 6 to 9 percent range. F/T conditioning at this concentration yields excellent results at a generally acceptable cost.

*Energy Cost*

Operation and Maintenance Cost - Freezing of residuals involves significant energy input. This economic analysis is based on observation of freezing demonstrations and industry experience with ice-making systems. The basic parameters for energy evaluation are the number of kilowatt-hours required to freeze 1 ton of residuals and the local cost of energy in cents per kilowatt-hour. This evaluation is based on an energy consumption rate of 24 kWh per ton of ice for the BIOFREEZE™ and 80 kWh per ton of ice for the block freezer. The cost of the electricity is estimated at a unit cost of 7 cents per kWh, and this equates to a cost of $1.68 per ton of ice produced by the BIOFREEZE™ process and $5.60 per ton by the block freezer. Additional energy consuming components (recirculating and refilling pumps, crushing equipment, etc.) are included in the overall energy factor for the block system, but they have not been considered for the BIOFREEZE™.

Maintenance Costs - Properly maintained residuals freezing and refrigeration systems can be expected to provide many more years of service than the typical 10-year period assumed for economic evaluation. Frequently, annual maintenance costs are estimated as a percentage of total plant equipment cost, which has generally proven to be realistic and reasonable values.

**Case Study**

In order to evaluate the economics of a freeze/thaw system, the following case study was developed.

The water treatment plant is a conventional surface water treatment facility with a permitted capacity of 24 mgd. The treatment process consists of rapid mixing, flocculation, sedimentation, filtration, and disinfection. Alum and carbon are added to the raw water for coagulation and adsorption of taste and odor causing compounds.

Residuals are collected from the sedimentation basins and conveyed to batch operated gravity thickeners. The residuals are thickened to a solids concentration of 1 to 6 percent with an average of 3 percent. Sludge volumes range from 168,000 to 486,000 gallons per month, with an average of 312,300 gallons per month.

Currently, thickened residuals are trucked to a landfill for ultimate disposal. Tipping fee at the landfill is $80/wet ton.

Three alternatives were developed for the management of the water treatment residuals: installation of a belt filter press, a block mechanical freeze/thaw system with a belt filter press, and a BIOFREEZE™ mechanical freeze/thaw system with a belt filter press.

*Alternative 1 - Belt Filter Press*

Under this alternative, thickened solids would be pumped to a belt filter press for dewatering. Facilities would be provided to add polymer to the residuals ahead of the belt press. Dewatered cake would be conveyed to a covered truck loading station.

Belt press equipment, polymer feed equipment, and controls would be installed in a 45-ft by 45-ft building attached to the covered truck loading station.

*Alternative 2 - Freeze/Thaw Using Vertical Plate Block Freezers with Thickening*

Under this alternative, solids would be pumped to a thickening unit for thickening. The thickened solids would be pumped to the freezer and controls would be installed for filling the freezer automatically. An ammonia refrigeration system would be provided for freezing the solids. Heat recovery would be provided to reduce energy use. After the freezing process, the block of frozen residuals would be put through an ice crusher followed by primary separation equipment. This equipment would be used for the initial separation of the conditioned solids from the liquid. The solids would flow by gravity to a belt filter press for dewatering. The dewatered cake would be conveyed to a covered truck loading station.

The equipment for this alternative would be installed in a two-story building. Freezing equipment would be installed on the second floor and the belt press equipment on the first floor.

*Alternative 3 – Freeze/Thaw Using BIOFREEZE™ with Thickening*

Under this alternative, solids would be pumped to a thickening unit for thickening. The preconditioned solids would be pumped to the BIOFREEZE™ and controls would be installed for filling the freezer automatically. A refrigeration system would be provided for freezing the solids. An ice crusher will not be needed for in the BIOFREEZE™ process since the thawing of the frozen residuals takes place in the same channels as they were frozen in. Primary separation equipment would be used for initial separation of the conditioned solids from the liquid. The solids would flow by gravity to a belt filter press for dewatering. The dewatered cake would be conveyed to a covered truck loading station.

The equipment for this alternative would be installed in a two-story building. Freezing equipment would be installed on the second floor and the belt press equipment on the first floor.

Construction Cost - Building costs were estimated based on $100/sq ft for a single story building and $150/sq ft for a two-story building, assuming concrete block and brick construction. Costs for site work, electrical and instrumentation work, and contractors general requirements were assumed to be 15 percent of the subtotal. Contingencies and engineering were assumed to be 20 percent and 15 percent of the subtotal, respectively.

Operation and Maintenance - Operation and maintenance costs (Table 10) were projected using information from the four demonstration locations and personal communications with personnel of other treatment facilities. It was assumed that all three alternatives would be operated 24 hours per day, 5 days per week. Power costs were projected from the electrical data provided by manufacturers and a unit cost of $0.07/kWh. Annual maintenance costs were based on manufacturers' recommended costs and BV experience with similar projects. Labor costs were developed assuming one full-time operator 8 hours per day for each alternatives, at a cost of $25/hr. Hauling costs at $9.00/cubic yard were developed from information gathered from the four demonstration locations. Tipping fees quoted by landfills at various locations in the U.S. ranged from $30 to $110/wet ton. A value $80/wet ton was used in the analysis.

**Table 10: Annual Operation and Maintenance Costs**

| O&M Maintenance Costs $/Year | Alternative 1 Belt Filter Press $ | Alternative 2 Thickening, Block Freezer $ | Alternative 3 Thickening, BIOFREEZE™ $ |
|---|---|---|---|
| **Power** | 1,000 | 16,712 | 5,914 |
| **Polymer** | 5,110 | 1,022 | 1,022 |
| **Maintenance** | 5,271 | 10,364 | 8,827 |
| **Labor** | 26,000 | 26,000 | 26,000 |
| **Transport** | 15,029 | 7,665 | 7,665 |
| **Disposal** | 113,556 | 51,100 | 51,000 |
| **Total** | $165,699 | $112,864 | 100,528 |

*Present Worth Analysis*

A present worth analysis was performed assuming a 10-year design life and 8.5 percent interest. Table 11 shows the results of this analysis.

**Table 11: Present worth Analysis**

| | Alternative 1 Conventional Disposal $ | Alternative 2 Thickening, Block Freezer Conditioning, Belt Press Dewatering and Disposal $ | Alternative 3 Thickening, BIOFREEZE™ Conditioning, Belt Press Dewatering and Disposal $ |
|---|---|---|---|
| **Construction Cost** | 1,009,200 | 1,692,875 | 1,536,855 |
| **Present Worth of O&M 10 Years, 8.5% Interest** | 1,088,963 | 740,537 | 659,600 |
| **Total Present Worth** | 2,098,163 | 2,433,412 | 2,196,455 |

The results of the present worth analysis indicate that the freeze/thaw process will be cost-competitive only if the thickening step is incorporated into the process. Freeze/thaw without pre-conditioning does not appear to be cost-effective.

### 2.6.4.3. Recommendations

Additional demonstration testing needs to be completed to verify the results of previous testing. The testing should concentrate on the thickening step to verify the assumptions used in this report.

The results of this round of testing confirm that F/T technology is effective in dewatering inorganic water treatment sludges. According to the present worth analysis, the BIOFREEZE™ energy recovery method appears to be similar to conventional disposal methods. Additional demonstration studies are required to verify the assumptions used in the analysis. Capital costs are a significant obstacle for application of F/T. It is recommended that additional freezing systems be evaluated to determine if the capital costs can be reduced.

For the biological sludges, the BIOFREEZE™ system appears to be able to provide substantial benefits to anaerobic digestion. Further testing needs to be completed to confirm that increased methane production can be achieved and to what extent dewaterability of the sludges can be expected. At larger wastewater plants that use cogeneration, it is possible that the potential increase in methane production could alone pay for the operating costs of the F/T system. It is recommended that EPRI pursue additional studies coupling F/T with anaerobic digestion.

Brine reject is a growing concern nationwide as RO treatment of potable water increases. Results achieved from this study on F/T of brine were inconclusive, however, previous work in this area appears promising. It is recommended that EPRI investigate developing the BIOFREEZE™ system operating parameters and/or other freeze concentration technologies in order to optimize the FC process.

#### 2.6.4.4. Benefits to California:

The vast majority of wastewater treatment plants in California use biological treatment, either in the form of activated sludge or trickling filters. In the biological treatment process, not only are particulates in the wastewater removed for disposal, but also excess biological growth. This wastewater residual can then be added to anaerobic digesters for stabilization. After digestion, many plants then dispose of this residual by land application or in landfills. The freeze-thaw process can be used to condition the biological residual before anaerobic digestion. The benefits from the use of this technology include:

- Increased methane generation capacity – methane recovery would enable plants to provide additional cogeneration capacity, thereby, reducing total electric system requirements statewide and increasing the quantity of power generated using "green methods".
- Increased dewaterability of sludge – additional volume reduction of wastewater residuals will reduce the landfill capacity needed for disposal of residuals and afford more landfill space in the state for municipal purposes.

Membrane technology is gaining popularity throughout the water and wastewater industries in the state of California. Membranes effectively treat water to levels that previously were almost unattainable; however, like any treatment process, it generates a waste that must be handled. This waste consists of a concentrated solution of dissolved particles that are referred to as brine. Presently, disposal of this waste may be a costly proposition depending on the location of the treatment plant. The benefits from the use of this technology include:

- Reduce the amount of salt to be disposed in landfills – this will reduce the landfill capacity needed for disposal and afford more landfill space in the state.
- Reduce the amount of salt to be disposed by ocean discharge – this will reduce the risk of environmental degradation from ocean discharges of brine.

In California, chemicals such as alum, ferric chloride, and lime are typically added to the liquid stream to remove particulates from raw water at water treatment plants,. Chemicals combine with the solids in the raw water to form larger particles that can be settled out of the water. The settled particles become water residuals when they are removed from the process. Presently, these residuals are often disposed of in receiving streams or in sanitary sewers. One way to lower the cost of residual disposal is to reduce its volume. The benefits from the use of this technology include

- Increase the dewaterability of water plant residuals – additional volume reduction of residual will reduce the landfill capacity needed for disposal and afford more landfill space in the state.

## 2.7. Task 2.7 Perform Energy and Process Assessment

### 2.7.1. Objectives

This report summarizes the findings of four separate energy assessments conducted at water and wastewater treatment plants in California. The plants evaluated included:

- San Francisco's Harry Tracy water treatment plant
- Metropolitan Water District's Jensen filtration plant
- Union Sanitary District's wastewater plant
- Vallejo Sanitation and Flood Control District's wastewater plant.

The purpose of the assessments is to identify opportunities to reduce energy consumption within the facilities and electrotechnologies that could improve the treatment process. The objective is to develop energy conservation measures to obtain the potential reductions and to evaluate the benefits of any electrotechnologies cited.

### 2.7.2. Approach

This project involved four separate energy assessments conducted at water and wastewater treatment plants in California. The purpose of the assessments is to reduce electrical demand in the water and wastewater treatment plants evaluated. The objective is to develop energy conservation measures to achieve the reduction in electrical demand and to evaluate the benefits of any electrotechnologies cited. This report summarizes the four assessments, which are included in the appendices.

Each of the facilities assessed in this project were visit by the project team members. During the site visits the project team met with the plant staff for an orientation, a site tour, and to gather historic plant data. From discussions with members of the staff, the data collected, and the observations made from the tour, energy conservation measure (ECMs) were developed. A report evaluating the ECMs and the team's recommendations was then written for each facility.

### 2.7.3. Outcomes

*Water Treatment Plants*

The Harry Tracy water treatment plant uses conventional flocculation/sedimentation with filtration and ozone to treat an average flow of 56 mgd. Raw water is pumped from the Hetch Hetchy water system into the plant and treated water flows out by gravity. The Jensen water plant treats an average daily flow of 200 mgd with a total plant capacity of 750 mgd. The treatment process also uses conventional flocculation/sedimentation with filtration and disinfection. Both raw and treated water flow by gravity result in a low unit energy consumption. Table 12 summarizes the energy consumption and cost for each plant.

**Table 12: Energy Summary for Water Treatment Plants**

| | Jensen | Harry Tracy |
|---|---|---|
| **Annual Plant Production** | 73,637 Mgal | 20,587 Mgal |
| **Average Daily Flow** | 200 mgd | 56 mgd |
| **Annual Energy Cost** | $446,559 (8.3¢/kWh) | $556,707 (6.05 ¢/kWh) |
| **Total Identified Savings** | $68,200 (15%) | $45,800 (8%) |
| **Annual Energy Consumption** | 5,404,000 kWh | 9,199,755 kWh |
| **Billing Demand** | 800 kW – 1,120 kW | 1,280 – 2,410 kW |
| **Specific Unit Energy Consumption** | 74 kWh/Mgal | 446 kWh/Mgal |

Table 13 summarizes the energy conservation measures (ECMs) recommended for each water plant. Eleven ECMs were recommended for implementation. The ECMs include three lighting retrofits to improve efficiency and control, an energy management systems, load shedding three systems during peak hours, modifications to improve the equipment efficiency of three processes, and an HVAC change to reduce cooling. The ECMs identified could result in a reduction of over 1,250,000 kWh annually, which would save over $132,000.

**Table 13: Summary of ECMs for Water Treatment Plants**

| Type of ECM | Number | Energy Savings (kWh) | Annual Cost Savings | Potential Rebates | Estimated Capital Cost | Recommended |
|---|---|---|---|---|---|---|
| **Lighting Retrofits** | 3 | 47 kW 267,624 kWh | $18,540 | $24,942 | $53,943 | YES |
| **Energy Management System** | 1 | 100 kW 0 kWh/yr | $12,300 | | $25,000 | YES |
| **Load Shifting** | 3 | 426 kW 0 kWh/yr | $44,900 | | $3,000 | YES |
| **Equipment Modifications** | 3 | 321 kW, 911,880 kWh/yr | $53,100 | $111,902 | $49,250 | YES |
| **HVAC Changes** | 1 | 0 kW, 72,000 kWh/yr | $3,700 | | $2,000 | YES |
| **Total of Recommended ECMs** | | | $132,540 | $136,844 | $133,193 | |

*Wastewater Treatment Plants*

Union Sanitary District's wastewater plant treats an annual average flow of 30 mgd. The treatment process uses conventional activated sludge, chlorine disinfection, anaerobic digestion and belt filter presses. Vallejo's wastewater plant treats an annual average flow of 12.4 mgd. The treatment process uses biofilters, aeration basins, both UV and chlorine disinfection, lime stabilization, and belt filter presses. Both facilities pump their effluent to the bay. Table 14able 2.14 summarizes the energy of each plant.

**Table 14: Energy Summary for Wastewater Treatment Plants**

| | USD | Vallejo |
|---|---|---|
| **Plant Flow** | 10,975 Mgal | 4,526 Mgal |
| **Average Daily Flow** | 30 mgd | 12.4 mgd |
| **Total Electricity Cost** | $1,007,422 (5.54¢/kWh) | $600,244 (5.7¢/kWh) |
| **Total Identified Savings** | $338,540 (33%) | 93,900 (15.6%) |
| **Unit Energy Consumption** | 1,657 kWh/Mgal | 2,263 kWh/Mgal |
| **Annual Energy Consumption** | 18,184,050 kWh | 10,243,206 kWh |
| **Cogenerated Power** | 1,551,561 kWh | Ø kWh |
| **Billing Demand** | 2,630 kW – 3,200 kW | 1,600 kW - 2,900 kW |

Table 15 summarizes the energy conservation measures identified for both facilities. Twelve ECMs were recommended for implementation. The ECMs include two lighting retrofits to reduce lighting and improve control, two energy management systems, operational changes to two processes, modifications to two non-potable water systems to reduce load, equipment modifications to improve efficiency, load shedding during peak hours, changes to a cogeneration system, and a change to a discharge permit to lower demand. The ECMs identified could result in a reduction of over 7,281,000 kWh annually, which would save over $432,000.

**Table 15: Summary of ECMs for Wastewater Treatment Plants**

| Type of ECM | Number | Energy Savings | Annual Cost Savings | Potential Rebates | Estimated Capital Cost | Recommended |
|---|---|---|---|---|---|---|
| Lighting Retrofits | 2 | 10 kW<br>135,300 kWh | $8,640 | $14,884 | $20,000 | YES |
| Energy Management System | 2 | 320 – 380 kW<br>0 kWh | $25,400 | | $40,000 | YES |
| Operational Changes | 2 | 75 kW<br>803,000 kWh | $44,800 | $35,640 | $30,000 | YES |
| Modify NPW System | 2 | 19 kW<br>762,120 kWh | $42,000 | $91,090 | $42,000 | YES |
| Equipment Modifications | 1 | 41 kW<br>29,930 kWh | $1,700 | $2,693 | $1,000 | YES |
| Load Shedding | 1 | 75 kW<br>58,500 kWh | $4,900 | $5,265 | $0 | YES |
| Cogen Changes | 1 | 600 kW<br>4,600,000 kWh | $254,000 | $180,000 | $205,000 | YES |
| Permit Changes | 1 | 127 kW<br>893,500 kWh | $51,000 | $80,415 | $150,000 | YES |
| Total of Recommended ECMs | | | $432,440 | $409,987 | $488,000 | |

### 2.7.4. Conclusions and Recommendations

#### 2.7.4.1. Conclusions

This project has shown energy assessments to be an effective way to reduce electrical demand and costs at municipal water and wastewater facilities. Several opportunities exist at water and wastewater facilities that could result in further reduction in the state's electrical demand.

#### 2.7.4.2. Commercialization Potential

No products were developed as a result of this work. The goal of an energy assessment is to reduce electrical consumption and operating costs. Energy assessments range in cost from approximately $10,000 to $50,000 per facility. The assessments typically identify three to five times the cost in annual energy savings.

#### 2.7.4.3. Recommendations:

It is recommended to implement the ECMs identified in this project and to conduct new studies at other facilities throughout the state to further reduce electrical demand and conserve our natural resources

#### 2.7.4.4. Benefits to California:

The State of California benefits by the conservation of natural resources, reduction in pollution, minimized costs, and improved quality of treatment which thereby protects the environment. Eleven energy conservation measures (ECMs) at the water plants and 12 at the wastewater plants were identified through this project. These ECMs are estimated to save 8,533,854 kWh annually, which produces a cost savings of approximately $564,580. Table 16 summarizes the ECMs.

**Table 16: Summary of ECMs**

| Type of ECM | Number | Energy Savings (kWh) | Annual Cost Savings | Potential Rebates | Estimated Capital Cost | Recommended |
|---|---|---|---|---|---|---|
| Lighting Retrofits | 5 | 51 kW<br>402,924 kWh | $27,180 | $39,826 | $74,000 | YES |
| Energy Management System | 3 | 420 - 480 kW<br>0 kWh/yr | $37,300 | | $65,000 | YES |
| Load Shifting | 4 | 501 kW<br>58,500 kWh/yr | $49,800 | 5,625 | $3,000 | YES |
| Equipment Modifications | 4 | 362 kW,<br>941,810 kWh/yr | $54,800 | $114,595 | $50,250 | YES |
| HVAC Changes | 1 | 0 kW,<br>72,000 kWh/yr | $3,700 | | $2,000 | YES |
| Operational Changes | 2 | 75 kW<br>803,000 kWh | $44,800 | $35,640 | $30,000 | YES |
| Modify NPW System | 2 | 19 kW<br>762,120 kWh | $42,000 | $91,090 | $42,000 | YES |
| Cogen Changes | 1 | 600 kW<br>4,600,000 kWh | $254,000 | $180,000 | $205,000 | YES |
| Permit Changes | 1 | 127 kW<br>893,500 kWh | $51,000 | $80,415 | $150,000 | YES |
| **Total of Recommended ECMs** | | | $564,580 | $547,191 | $621,250 | |

## 2.8. Task 2.8 – Scale-up Issues

### 2.8.1. MWD Study --Task 2.8 – Scale-up Issues

#### 2.8.1.1. Objectives

- Evaluation of preliminary scale-up issues by assessing operational and water quality needs that impact design criteria for construction of a large-scale UV systems
- Microbiologically challenge the UV reactor so that its performance can be characterized in terms of transferred UV dose (as related to exact UV dose measured at the bench-scale)
- Monitoring of the UV reactor over a period of testing to evaluate process performance
- Determine the element productivity, ion selectivity, fouling potential, and cleaning cycle of 16-in. and 8-in.-diameter RO elements
- Provide an economic analysis of a full-scale RO plant utilizing 8-in. versus 16-in. diameter elements

#### 2.8.1.2. Project Approach

*Pretreatment*

Pretreatment for both the UV and RO technologies was provided by Metropolitan's demonstration-scale plant in La Verne, California. Water was pre-ozonated (0.95 mg/L ozone) in an over/under-baffled contactor to meet Surface Water Treatment Rule disinfection requirements. Coagulant (2-4 mg/L ferric chloride) and cationic polymer (1.0 mg/L) were fed at a flash-mixer prior to the flocculation basin. The water then passed through a sedimentation basin and a biologically-active anthracite/sand dual-media filter (5.1 gal/min/ft$^2$ loading rate).

*UV Disinfection*

A 3-mgd, medium-pressure, enclosed-pipe UV reactor was tested on the demonstration scale. Data on the performance of UV lamp sensors were collected along with water quality data for the water treated by the reactor. Biodosimetry experiments with MS-2 coliphage were also conducted to characterize the UV dose within the reactor.

*Reverse Osmosis*

A 200-gpm RO unit equipped with two pressure vessels operated in parallel was used to evaluate a large-diameter 16-in. diameter x 60-in. length RO element and a conventional 8-in. x 40-in. element. Both RO elements were spiral-wound and comprised of thin-film composite, polyamide membrane material. The 16-in.-diameter element was a new, experimental RO element with approximately 1,950 ft$^2$ of effective surface area, approximately 5 times the surface area of a traditional 8-in. element. Both RO elements were operated at 15 gallon/ft$^2$/day (gfd) flux and 14-15 percent water recovery which are levels that would be seen in a full-scale system operating at 85 percent recovery.

Based on operational data collected using both membrane elements, a hypothetical 185-mgd RO treatment plant was modeled to produce low-TDS water. The location of the desalting facility was assumed to be at an existing conventional water treatment plant with sufficient available space; therefore, only the capital and operation and maintenance costs associated with the RO facility were considered.

#### 2.8.1.3. Outcomes

*UV Disinfection*

Biodosimetry challenges were conducted with MS-2 coliphage. Challenge results coupled with weekly monitoring of inactivation of heterotrophic bacteria showed that the UV reactor provided adequate disinfection of biofilter effluent, as seen in Figure 2.12. In the range of water quality studied, 75 percent of the reactor capacity (3 of 4 lamps) were able to provide a low-pressure equivalent dose of 50 $mJ/cm^2$. With 2 to 4 lamps on, bacteria were consistently reduced by more than 3 $\log_{10}$. However, since these indicators were not monitored during water quality upsets, it is not known if this disinfection level was compromised.

This study showed that if UV technology is to be implemented to treat drinking water, improvements are needed in reactor monitoring and validation techniques. This study began to evaluate correlations between sensor reading and calibrated radiometer reading. Results indicate a linear relationship between the two. However, this relationship needs to be further characterized over a wider range of water quality (e.g., turbidity from 0.1 to 10.0 NTU) to understand sensor reliability for both filtered and unfiltered water applications.

Although this study showed successes in microbial challenges of the UV reactor, results will need to be verified at larger scales. Alternatives to biodosimetry need to be explored so that large California utilities may have other UV reactor dose-characterization options.

*Large-Scale Reveres Osmosis Desalination*

A 16-in. diameter RO element was operated in parallel to a conventional 8-in. diameter element for over 2,500 hours. The specific flux of the 16-in. element (0.23 gfd/psi) was 20 percent lower than the average specific flux of the 8-in. element (0.28 gfd/psi). Both elements were cleaned twice within 2,500 hours of operation. Both elements removed greater than 98 percent of the influent TDS. Differences in the performance of the two elements were attributed to design issues associated with the 16-in. element: excess membrane leaf length, inability to accurately measure the membrane surface area, and the prototype nature of the membrane manufacturing process.

Table 17 presents the results of the potential cost savings associated with the use of 16-in. diameter elements over 8-in. diameter elements for a 185-mgd RO plant. The large-diameter 16-in. elements are estimated to reduce RO plant capital costs by nearly 24 percent and overall costs (capital costs and O&M costs) by approximately 10 percent (the overall cost savings assumed that a second-generation element with improved flux would be designed). Brine disposal costs were not included in the analysis, but costs would be the same for either membrane size. The reduction in capital costs was mainly due to reducing the overall number of RO skids, as well as reducing the train piping, and support frames. The increased skid capacity resulted in better economy-of-scale for RO skid instrumentation and membrane feed pumps. The use of large-diameter elements also reduced the overall plant footprint which resulted in a 24 percent savings for the building costs, as well as savings on system-wide controls and electrical equipment.

**Table 17: Cost Comparison for 185-mgd Desalting System (8” & 16” Reverse Osmosis Elements)**

| | Reverse Osmosis Element Size | | Savings (%) |
|---|---|---|---|
| | 8-in. | 16-in. | |
| **Cost Component** | | | |
| **Annual O&M ($M/year)** | 19.4 | 20.8 (19.3*) | -7.2 (0) |
| **Total Capital RO Cost ($M)** | 170.6 | 130.2 | 24 |
| **Annual RO Capital Cost ($M/year)** | 14.9 | 11.4 | 24 |
| **Total Annual RO System Cost ($M/year)** | 34.3 | 32.2 (30.7*) | 6 (10) |

*Data in parentheses assumes second-generation prototype elements with improved specific flux.

### 2.8.1.4. Conclusions and Recommendations

**Conclusions**

If UV technology is to be used for municipal drinking water treatment, improvements in reactor monitoring and validation techniques are needed. This study developed a cursory correlation between sensor readings and calibrated radiometer readings which showed a linear relationship over the range studied (Figure 12). This relationship needs to be characterized over a wider range of water quality (e.g., turbidity from 0.1 to 10.0) to understand sensor reliability for both filtered water and unfiltered water applications. Although this study showed successes in microbial challenges of the UV reactor, larger-scale reactors will require validation. Alternatives to biodosimetry need to be explored so that large California utilities may have other UV reactor dose-characterization options.

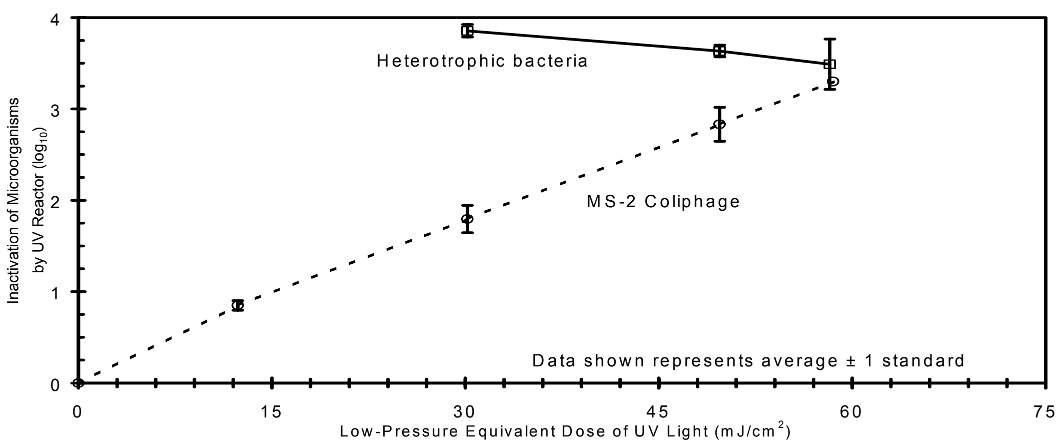



**Figure 12: Dose Response for Microbial Inactivation using Low-Pressure Equivalent UV Dose**

Large-diameter RO elements look very promising in reducing RO desalination costs for large-scale applications. Evaluation of one of the first 16-in. diameter prototype elements revealed that inefficiencies in the design currently exist. However, as work is continued with membrane manufacturers, the efficiency of the 16-in. element is expected to improve.

**Commercialization Potential**

*UV Disinfection*

Currently, UV reactors are manufactured by a number of companies and are now being marketed in the drinking water industry. However, due to shortfalls in technology performance (outlined in this report), widespread use of UV treatment in drinking water may not spread quickly.

*Large-Diameter RO Elements*

Currently, large-diameter elements of 16-in. or larger are not commercially available due to the following factors: 1) a high demand for large-diameter elements currently does not exist, 2) membrane manufacturers do not have the necessary capital equipment to mass-produce large elements, and 3) difficulties in handling larger-diameter elements must be resolved. However, as desalination plants continue to grow in number and capacity to meet growing demand and limited water resources, large-diameter elements are expected to become more attractive and cost-effective than conventional RO elements.

**Recommendations**

It is recommended that this study be followed with research evaluating the effects of water quality and water treatment chemicals on UV disinfection and alternatives to microbial biodosimetry in characterizing UV reactor dose. Characterization of sensor readings to a known standard (i.e., radiometry) should also be continued.

A second-generation 16-in. diameter element should be developed and tested to eliminate the inefficiencies observed in the first prototype element. Improvements in membrane design and optimization of the pretreatment process will help improve membrane productivity and fouling, which minimizes both capital and O&M costs. An important issue that will need to be addressed in the future is the loading and unloading of the membranes. A dry 16-in.-diameter element weighs approximately 200 lbs and when wetted, an individual element can weigh over 300 lbs.

**Benefits to California**

UV treatment of drinking water could be a great benefit to California by allowing a relatively low-cost technology to provide enhanced disinfection and protection of public health. However, significant advances are needed in UV sensor technology, UV dose characterization (i.e., validation techniques such as biodosimetry), and methods in combining these two issues to provide consistent, reliable reactor monitoring before safe and reliable implementation can be expected.

The development of large, 16-in. diameter elements will benefit the entire state of California by lowering the cost of desalination and reducing the energy requirements to treat brackish water. The successful development of these large-diameter elements will help to significantly lower cost of new, large-scale desalination facilities (greater than 100 mgd) by taking better advantage of economies of scale.

### 2.8.2. OCWD Study -- Scale-up Issues

#### 2.8.2.1. Objectives

The objective of the scale up study was to evaluate the performance of a microfiltration system on a scale that yields useful design information for municipal wastewater reclamation projects. To this end several investigations were initiated to answer the following critical design questions for large-scale reclamation applications:

- Is it possible to increase the output of a MF module by increasing the surface area without increasing the module cleaning requirements?
- How important is prechlorination in the control of microbial fouling on the membrane surface?
- What is the effective process recovery of MF system consisting of multiple modules (What volume of waste is produced per volume of water treated)?

- How often is it necessary to clean a MF system that consists of multiple modules and what is the most effective cleaning solution?
- What are the energy requirements for a system consisting of multiple membrane modules?
- Is it necessary to install the system in a building or can the materials used to construct a multiple MF system stand up to repeated exposure to sunlight, wind and rain?

#### 2.8.2.2. Project Approach

- Two microfiltration modules, the PALL-5 inch diameter and the USV-6 inch diameter were used in the scale up studies. Both modules used identical hollow fiber polyvinylidene fluoride membranes with a nominal pore size of 0.1 microns.
- The modules were installed in pilot and demonstration scale microfiltration (MF) systems at OCWD's Water Factory 21 facility. The MF systems operated on clarified effluent from an air activated sludge process.
- The experimental design was based on monitoring performance of a pilot scale system, containing four of the smaller modules, rated at 36 gpm compared with that of a 600 gpm demonstration scale system.
- The pilot system contained four PALL 5023 modules. Clarified secondary effluent, containing a 3-5 ppm combined chlorine residual, was screened through a 120 micron filter and stored in a feed tank mounted on the unit. A dedicated feed pump provides driving force for the process. The pump discharges into a single feed header that connects to the bottom of each module. The pressurized effluent enters the module and contacts the outer surface of the individual hollow fiber membranes. Microfiltered filtrate passes across the membrane and collects on the inside (or lumen) of the fiber while suspended solids, bacteria and fine colloids are retained on the outer (or shell) membrane surface. Filtrate was collected in a dedicated 50 gallon tank which served as a reservoir for backwash water. The recirlculation rate was controlled via a flow control loop consisting of a flow meter on the reject manifold connected to the pneumatic valve. Retained solids are dislodged from the membrane surface at preset time intervals by either scouring the membrane with air bubbles, reversing the flow of filtrate across the membrane or a combination of the two. The System operates as a continuous process at a constant flux between backwashes.
- The demonstration system components were installed and assembled over a three month period between January and March, 1999. The MF system consisted of fifty USV 6023 modules arranged in two rows of twenty five. At the end of the test period the outer surface of the modules were examined to assess the potential damage caused by exposure to direct UV light.
- The mode of operation for the demonstration system was identical to the pilot in all respects with the exception of the chlorine addition system. Start-up issues were addressed for three months following the installation of the system (April 1999 to June 1999). These issues included: programming of computer control

system, fine tuning of valve operation, and optimization of air flow from the compressed air system.

- The pilot and demonstration systems were operated in tandem. The bulk of the data was collected from the demonstration scale system to establish performance criteria; the pilot system was to be operated to compare the fouling rates of the 5-inch and 6-inch modules and determine the impact of chlorination on performance.
- The overarching objective of these experiments was to identify the optimum backwash combination for a scaled up system. The performance of the demonstration system was evaluated under three backwash scenarios:

Scenario A - Aggressive backwash conditions consisting of reverse flow every fifteen minutes and an air scour every 30 minutes.

Scenario B - Moderate backwash conditions consisting of reverse flow every twenty minutes and air scour every 40 minutes.

Scenario C - Benign backwash conditions consisting of reverse flow every thirty minutes and air scour every sixty minutes

Three alternative backwash combinations were investigated under each scenario.

- The chemical cleaning procedure for the demonstration system consists of recirculation of a citric acid solution through the membranes for a period of time followed by a soak of the membranes in the citric acid solution. After the citric acid portion of the cleaning is complete the same procedure is done using a caustic solution (sodium hydroxide). This cleaning procedure was used during the first six months of operation (June 1999 to December 1999).
- During the next three months (January 2000 to March 2000) a different cleaning procedure was used. The caustic cleaning step was done before the citric acid cleaning step. The concentration of caustic solution was increased to 2% with an increased chlorine concentration of 5000 ppm. The caustic solution was recirculated through the membranes for 2 to 3 hours and allowed to soak on the membranes overnight. After the overnight soak in caustic solution the citric acid cleaning step occurred. The citric acid solution was recirculated through the membranes for 2 to 3 hours and then allowed to soak on the membranes for 1 to 2 hours.
- Beginning in March 2000 a third cleaning procedure was implemented. The new cleaning procedure remained in effect until the end of the test period. This procedure consisted of a 2% caustic solution with 5000 ppm chlorine being recirculated through the membranes for 10 to 12 hours and then the solution was rinsed without a soak step. The membranes were then subjected to a citric acid cleaning. A 2% citric acid solution was recirculated through the membranes for 2 to 3 hours and then rinsed without a soak step.

#### 2.8.2.3. Outcomes

- It is possible to increase the output of a MF module by increasing the surface area without increasing the module cleaning requirement.

- Adequate contact time during pre-chlorination is essential for the control of microbial fouling of the membrane surface.
  The pilot and the demonstration systems operated at the same flux (loading rate) on clarified secondary effluent. Under loading rates the 6″ module appeared to reach critical transmembrane pressure and foul faster than the 5″ module. The 6″ module fouled at approximately 3 times the rate (1.76 psi/day) as the 5″ module (0.58 psi/day).
- The overall process recovery of the full-scale Pall microfiltration system was found to be 90% at a flux of 24 gal/$ft^2$/day (gfd).and a backwash interval of 15 minutes.
  For microfiltration to be an effective pretreatment process for the reverse osmosis system membranes should operate continuously for a minimum of 21 days without chemical cleaning. After the first 30 days of operation, neither the benign (air scour every 60 minutes) or moderate (air scour every 40 minutes) backwash protocols were effective in controlling fouling. A cleaning interval of 21 days was only achieved after the loading rate on the membranes was reduced by 25% from 12 gpm/module to 9 gpm/module which was equivalent to a flux of 24 gfd. Under these conditions the system operated at a recovery of 90% and it was possible to achieve a 21 day between cleanings when a specific cleaning protocol was employed. The backwash sequence was consolidated to have the air scour and reverse flush steps occur simultaneously every 22 minutes for 110 seconds. This step was then followed by 30 seconds of reverse flush alone. This set up also resulted in system recovery of 90%.
- The optimum cleaning procedure involved a caustic cleaning with a 2% sodium hydroxide solution and 5000 ppm chlorine followed by a acid cleaning using a 2% citric acid solution.
  The standard cleaning procedure for membrane systems is based on the use of a high pH step to hydrolyze organic molecules and low pH to remove inorganic species. A strong oxidant can also be introduced to the high pH clean to oxidize the retained organic compounds. Two variations on the low pH/high pH cleaning protocol were evaluated

The first cleaning protocol was based on a low pH step followed by a high pH step. The membranes were exposed to a 2% citric acid solution with 30 minutes of recirculation followed by a 60 minutes with no recirculation. The membranes were then exposed to a 0.5% caustic (sodium hydroxide) and 600 ppm chlorine solution for 30 minutes without recirculation. Results obtained using this cleaning protocol were erratic and inconclusive.

The second cleaning procedure reversed the order of the low pH and high pH cleanings. The strength of the caustic solution was also increased from 0.5% to 2% and the concentration of chlorine added to the caustic solution was increased from 600 ppm to 5000 ppm. The recirculation time of the caustic solution was increased from 30 minutes to 10 hours. The increase in recirculation time proved to be more effective in removing the fouling on the MF membranes than soaking. Also, the nature of the fouling on the MF membranes was found to be mainly organic which is caused by the accumulation of particulate and dissolved organic matter on the walls of the MF fibers. Organic fouling is removed by the caustic solution which was increased with recirculation. The new cleaning procedure allowed for a three week average cleaning interval for the Pall full-scale MF system.

- The amount of energy required by the full-scale Pall microfiltration system is 400 kWh per million gallons of water treated. This was calculated by tracking the electricity usage of the various components of the system which include the feed pump, reverse flush pump, compressed air system, heaters for the cleaning system and the computer control system.Major factors that affect energy usage of the MF system include: process recovery, cleaning intervals, and flux rate. Of these, the flux rate has the greatest effect on the energy required for microfiltration systems. For the Pall MF system a flux of 24.1 gfd was found to be ideal. The largest energy usage is for the feed pumps which, for an 80 mgd system , would require nearly 5.5 million kWh of energy per year.
- It is possible to operate a full scale system with some exposure to direct sunlight. Eight modules were installed on the full scale system that were coated with a special ultraviolet-resistant finish. The appearance of these specially coated modules was observed every month for obvious signs of deterioration. Over the course of a year and a half no deterioration was found on either the coated or the uncoated modules.

#### 2.8.2.4. Conclusions and Recommendations

**Conclusions**

- To meet the requirement established by OCWD for a three-week interval between chemical cleanings, an ideal process recovery for the full-scale MF system of 90% was established. The 90% recovery figure is ideal for a system flux of 24.1 gfd for operation on secondary effluent. The process recovery for the Pall MF system is largely dependant on the interval between the air scour and reverse flush processes. The testing at OCWD showed that a 22- minute interval was ideal and that the two processes occur at the same time. The exact settings for the two processes were also established as part of this testing. The settings established as part of this testing could be applied to other wastewater reclamation installations.
- The cleaning procedure for the Pall MF system can be varied by the amount, re-circulation time and soak time of the chemical. It was important to establish an effective cleaning protocol to meet the required three week cleaning interval. Once the cleaning procedure is established the space requirements for cleaning can be determined. The caustic portion of the cleaning was found to be more important than the acid portion, because majority of the fouling was found to be organic and not inorganic (mineral scale) fouling. This resulted in a nearly ten hour caustic solution re-circulation requirement as opposed to two hours of the acid re-circulation.

**Commercialization Potential**

This research testing established that the energy requirement for the MF is quite comparable with conventional reclamation treatment technologies. The added benefit of MF is that the water quality produced and the process space requirement is significantly less than that of conventional treatment. Most California municipalities are faced with space limitations and increasing demands for water due to population growth. MF has great potential for meeting future water needs of California by using a process that has a low space requirement, excellent effluent water quality, and a lower energy cost than conventional treatment processes.

**Recommendations**

Process recovery established here should be applicable to other future installations treating water with similar quality. Continued testing is needed, however, at the established process settings to verify long term validity. Also, water quality produced should be closely monitored to insure that long-term operation at these parameters will not result in quality decline. The microfiltration membrane integrity also needs to be observed over a long-term period. It is recommended that continued testing using the cleaning procedure established during testing occur. Procedures established here could be easily modified for other installations where water quality differ. The power requirements established during this testing should be further compared with those established elsewhere for MF processes as well as with other conventional treatment technologies such as chemical clarification or multi-media filtration.

**Benefits to California**

The benefit to California is the establishment of microfiltration technology as a viable alternative for large-scale wastewater reclamation. The use of MF technology will allow reclamation to occur with greater ease and reduce California's dependence on imported water sources. The long-term benefit of this project is the credibility and confidence gained in this technology for future reclamation projects because of the success achieved through this testing. The space requirements established are very beneficial to other California municipal reclamation agencies. In most cases the land required for MF is several times smaller than that of current reclamation treatment processes. This testing has established a good estimate of the power requirements of MF technology for wastewater reclamation. The power requirement established during this testing will allow other agencies to evaluate the MF process for use in their treatment applications.

### 2.8.3. Technology Transfer

As research breakthroughs and other important results were achieved, EPRI and AWWARF led an aggressive technology transfer effort including publishing technical information bulletins, organizing general information seminars, and conducting research needs assessment workshops to disseminate research findings to the municipal water community and related industries.

The information bulletins presented technical concepts in a reader-friendly format, incorporating graphics and easy-to-understand tables and charts. For consistency, the bulletins all had a common format with the following general sections:

- Summary and Purpose - a brief overview of the technology and results
- Background - a statement of the problem (environmental concern)
- Technology Overview - a brief description of the specific technology being used to address the problem
- Recent Research - a review of the current research project, current results, and implications of the results (future applications)
- Where to Find Out More - a brief list of reference documents and/or individuals

As part of Task 8, an extensive mailing list of potential concerned parties and stakeholders, including business, civic, environmental, agricultural, government, and consumer organizations, both within California and nationwide, were compiled. The mailing lists of the Municipal Water and Wastewater (MWW) Program, the CEC, the California Department of Water Resources, and the Water Resources Control Board, will provide a preliminary first step towards achieving this goal.

Because it is extremely important to emphasize communication between agencies and the general public, general information workshops were a major part of the technology transfer approach. The goal of the workshops was to present progress-to-date, exchange information, and obtain timely input. Three one-day workshops were held. The first workshop gathered input from industry experts, technology users, government agencies, and general participants to determine future workshop schedules and agendas. Workshop announcements, and a notification strategy, such as newspapers and trade journals, will be proposed at the first workshop. Since research results often have a significant impact on the direction of future projects, the remaining two technical workshops will be held in order to share technical information and chart-out future endeavors. It is hoped that a list of recommended future research projects will be produced from these workshops.

## 3.0 Project Summary Conclusions

This section compiled and summarized the study of six innovative water/wastewater treatment technologies and the assessments of energy and processes at four municipal facilities. In addition, the project provided scale-up studies of three of the six technologies and presented three technology transfer workshops. A detailed discussion of the above can be found in Section 2 of this report. The following is a summary conclusion of these tasks.

### 3.1. Task 2.1 – Investigate Advanced Oxidation Processes

#### 3.1.1. Pulsed UV

- UV reduced bromate more efficiently in laboratory waters than natural waters.
- UV alone could not effectively reduce MTBE;
- UV/$H_2O_2$ was effective in reducing MTBE;
- PEROXONE was more effective in oxidizing MTBE than ozone
- UV alone was effective in removing NDMA
- Ozone alone was ineffective in NDMA reduction in potable water
- PEROXONE improved NDMA removal efficiency compared to ozone alone
- Perchlorate was not reduced by UV
- UV reduced MIB and geosmin (Taste-and-Odor Compounds) by 92 and 97 percent respectively at a dose of 10,100 $mJ/cm^2$

### 3.2. Task 2.2 – Investigate Biological Denitrification

- Although pilot demonstration proved that biological denitrification was effective in nitrate removal, the City of Modesto, on December 20, 2000, decided to postpone the commercial-scale Grayson Biological Denitrification Project. Instead, the City elected to install a 1,000 feet deep-well in the area of the Grayson system to obtain water with nitrate below the government action level.
- EPRI was able to secure approval from the California Department of Health Services for a suitable test protocol for this process.
- Based on discussions with California DHS and other interested parties, the future Modesto pilot study will be conducted in two phases. First phase will consist of a one to three-month demonstration of a 6 to 10 gpm pilot system to be followed by a Phase 2 demonstration of a 300 gpm system.

### 3.3. Task 2.3 – Investigate Solids Removal Technologies

#### 3.3.1. MWD Study

*Pilot-Scale Results*

Despite each pretreatment tested (conventional treatment with and without ozone biofiltration and microfiltration), dramatic differences in RO performance was observed. The performance of conventional treatment was improved through the addition of pre-ozonation and operating the filters biologically active. Conventional treatment with ozone/biofiltration slowed the RO membrane rate of fouling by a factor of 2, even when. operated at higher flux. Microfiltration provided the highest quality water to the RO process and thus resulted in the lowest cleaning frequency.

*Full-Scale Results*

Conventional treatment using both aluminum sulfate and ferric chloride coagulation resulted in adverse membrane performance that would hinder full-scale implementation of RO technology. During RO testing using alum coagulation (6 to 8 mg/L), alum residuals (aluminum hydroxide) and colloidal clay materials (aluminum silicates) rapidly accumulated on the membrane surface and caused a loss in flux. However, salt rejection was largely unaffected. In contrast to alum, when ferric chloride (4 to 5 mg/L) was used as the primary coagulant, the specific membrane flux increased at the same time the salt rejection decreased.

*Economic Evaluation*

The project goal of reducing the overall treatment costs by 10 percent was met using conventional treatment as the pretreatment step to RO. However, high membrane fouling rates associated with using conventional treatment may reduce this option's feasibility. The addition of either ozone and biological filtration or MF lowered the RO capital costs, but increased the overall treatment costs due to the need to install new pretreatment equipment.

### 3.3.2. OCWD Study

- Correlations between membrane and module properties and membrane fiber failure (i.e., loss of integrity) were difficult to make because only two membrane fibers (the PM100s and PVDF fibers) underwent both materials testing and performance testing.
- Preliminary modeling results found the existence of additional stresses at the fiber/potting juncture which might possibly lead to the formation of fractures. Further modeling was impeded by limitations of the ADINA software.
- Although several ADINA updates were received over the course of the investigation and enhanced capabilities were to be forthcoming, the software never reached the initially stated potential. For this reason, current and future modeling efforts are focusing on more advanced software, ANSYS.

## 3.4. Task 2.4 – Investigate Salinity Removal Technologies

### 3.4.1. MWD Study

- With the development of polyamide membranes, not only has the operating pressures for membrane systems decreased, but the water production per psi has also increased substantially.
- Currently, NF membranes operate at significantly higher flux rates than RO membranes, but exhibit poorer salt rejection.
- This project only evaluated a small fraction of the total number of antiscalant types available for municipal water treatment. To facilitate information exchange

between research groups, a standardized antiscalant test protocol needs to be developed.

- Closed-loop membrane testing, while inexpensive, may not provide representative water quality conditions and single-pass, multi-array membrane systems are not only expensive but have high water flow rate demands (up to 20 gpm).

### 3.4.2. OCWD Study

*Chlorine Tolerant Membranes*

Long-term performance of the CPTC membrane was equal and possibly superior to traditional commercial membranes. While still in its developmental stage, this membrane can potentially treat high fouling water sources without compromising membrane integrity and performance as a result of fouling and chemical degradation.

*Brine Disposal*

The optimum temperature range for denitrification was determined to be between 20$^{o}$C and 40$^{o}$C. The total dissolved solid (TDS) concentration had insignificant effect on the denitrification rate. Preliminary laboratory-scale experiments revealed that the FBBR-GAC process is capable of removing approximately 45% of sulfate and 100% nitrate.

*IMANS™*

The initial testing of the IMANS™ process approach for wastewater treatment combined with water reclamation has shown promising results in terms of both sustainable performance and cost effectiveness. This process technology can potentially eliminate the secondary wastewater treatment step, lower life cycle costs, produce 50 percent less solids, and provide a smaller plant footprint.

## 3.5. Task 2.5 – Investigate Disinfection Alternatives

### 3.5.1. MWD Study

- The most susceptible organisms to UV light were found to be protozoa and heterotrophic bacteria, with UV dosages of less than 20 mJ/cm$^2$ providing 2 $\log_{10}$ inactivation.
- Organisms more resistant to UV light were the double-stranded RNA virus phi-6, followed by *B. subtilis* and then the single stranded RNA virus MS-2. For these organisms, a UV dose between 40 and 53 mJ/cm$^2$ was required to provide 2 $\log_{10}$ inactivation.
- The disinfection provided by UV on the human pathogen *G. lamblia* was even more effective than what has been previously reported for *G. muris* (Craik et al. 2000), a more easily handled rodent parasite.
- This task study shows that the process of using UV light to control post-filtration heterotrophic bacteria would need to be followed by a residual disinfectant such as chlorine or chloramines to provide a water with biological stability.

**CWD Study**

*Wedeco-Ideal Horizons TAK 55 System*

- The TAK 55 technology is capable of achieving 4-log MS2 inactivation.
- The pilot plant performance improved when the number of banks online was increased from 2 to 3 banks
- The maximum flow per lamp for achieving 4-log inactivation of MS2 was 12 gpm/lamp at low power set and 17.2 gpm/lamp at high power set for the filtered effluent, with a UV transmittance of less than 55 percent and turbidity greater than 1 NTU

*UV for Protozoa Inactivation*

- 4-log inactivation of B. *subtilus* spores was achieved at a dose of about 80 $mWs/cm^2$
- 4-log inactivation of G. *muris* was achieved at a dose of about 5 $mWs/cm^2$

*Pulsed UV*

- The pulsed UV testing on the OCWD secondary effluent source provided an excellent opportunity to investigate the effectiveness of the current chamber design on waters with low UV transmissivity and high NTU levels. By introducing a baffle design to reduce the effective cross section and improve mixing within the chamber, it was possible to adapt the Innovatech Pulsed UV system's drinking water design to effectively treat the secondary effluent to the desired four log reduction, for a very reasonable dose level of 80 $mWs/cm^2$.
- The testing using the special test chamber for flowing water testing showed that the use of pulsed UV for coliphage MS2 removal in tertiary effluent was not as effective as continuous-wave UV.

## 3.6. Task 2.6 – Investigate Solid Processing Techniques

- Mechanical F/T is extremely effective at reducing inorganic residual volumes, achieving up to a 94% reduction.
- Mechanical F/T of the wastewater biological residuals collected for this study did not produce the high level of separation achieved with the inorganic sludges.
- FC of RO brine did produce a concentrating effect, and reduce the volume of concentrated brine for disposal.
- Most of the power data collected during this study was inaccurate due to the BIOFREEZE™ unit not being insulated. The two trials that were conducted with the demonstrator insulated resulted in power consumption of 118.7 and 129.5 kWh/ton of frozen residual, which is very similar to data observed by EPRI.
- The economic analysis of the freeze/thaw method appeared to be cost competitive with conventional treatment of water residuals.

## 3.7. Task 2.7 – Perform Energy and Process Assessment

This project has shown energy/process assessments to be an effective way in reducing electrical demand and costs at municipal water and wastewater facilities. Several opportunities exist at water and wastewater facilities that could result in further reduction in the state's electrical demand.

## 3.8. Task 2.8 – Conduct Technology Transfer and Process Scale-Up for Commercial Deployment

### 3.8.1. MWD Study

- If UV technology is to be used for municipal drinking water treatment, improvements in reactor monitoring and validation techniques are needed.
- This study developed a cursory correlation between sensor and calibrated radiometer readings which showed a linear relationship over the range studied. This needs to be characterized over a wider range of water quality (e.g., turbidity from 0.1 to 10.0).
- Alternatives to biodosimetry need to be explored so that large California utilities may have other UV reactor dose-characterization options.
- Large-diameter RO elements are promising in reducing RO desalination costs for large-scale applications. Evaluation of one of the first 16-in. diameter prototype elements revealed that inefficiencies in the design currently exist.

### 3.8.2. OCWD Study

- To meet the requirement established by OCWD for a three-week interval between chemical cleanings, an ideal process recovery for the full-scale MF system of 90% was established. The 90% recovery figure is ideal for a system flux of 24.1 gfd for operation on secondary effluent. The process recovery for the Pall MF system is largely dependant on the interval between the air scour and reverse flush processes. The testing at OCWD showed that a 22- minute interval was ideal and that the two processes occur at the same time. The exact settings for the two processes were also established as part of this testing. The settings established as part of this testing could be applied to other wastewater reclamation installations.
- The cleaning procedure for the Pall MF system can be varied by the amount, re-circulation time and soak time of the chemical. It was important to establish an effective cleaning protocol to meet the required three week cleaning interval. Once the cleaning procedure is established the space requirements for cleaning can be determined. The caustic portion of the cleaning was found to be more important than the acid portion, because majority of the fouling was found to be organic and not inorganic (mineral scale) fouling. This resulted in a nearly ten hour caustic solution re-circulation requirement as opposed to two hours of the acid re-circulation.

## 4.0 Project Summary Recommendations

This section presents a summary of the major recommendations identified in the eight tasks. A full discussion of the recommendations can be found in section 2 of this report.

### 4.1. Task 2.1 – Investigate Advanced Oxidation Processes

Based on water quality issues and cost requirements, Pulsed UV can be used for the reduction of water contaminants. Although ozone may be less energy-intensive when compared to UV for several of the micropollutants studied, UV may be a more appropriate option based on disinfection by-product (DBP) formation potential. In considering these technologies, utilities must weigh energy and DBP costs prior to implementation.

### 4.2. Task2.2 – Investigate Biological Denitrification

Biological denitrification costs range between $0.55 and $1.40 per 1000 gallons. This range is comparable to ion exchange costs ($0.55 to $ 1.85) and reverse osmosis costs ($0.60 to $ 5.20), both per 1000 gallons. The broad range in costs for the conventional treatment technologies is the result of brine disposal and electricity costs, which vary depending on the location. In California, these disposal costs and power costs are expected to be on the high side of these ranges. Further, given California's recent power issues, any technology that conserves electricity, such as biological denitrification, will have inherent advantages over those that rely heavily on electricity, such as reverse osmosis. It is recommended that energy comparisons of these technologies be performed on commercial scale to fully assess the energy benefits of biological denitrification.

### 4.3. Task 2.3 – Investigate Solids Removal Technologies

#### 4.3.1. MWD Study

- Additional applied research is needed to optimize the conventional treatment process with and without ozone/biofiltration.
- Research is also needed to better understand the full effects of the interaction of different chemicals such as: coagulants (i.e. ferric, alum), disinfectants (i.e. chloramines), and antiscalants on the surface of the membrane.
- Utilities that are designing new desalination plants, microfiltration is the recommended optimal pretreatment technology which can provide the best feed water for RO membranes while minimizing fouling.
- Additional work with conventional treatment processes may also help water treatment plants use existing infrastructure as pretreatment to RO, thereby saving capital costs.

#### 4.3.2. OCWD Study

- Future efforts on microfiltration should include the evaluation of immersed hollow fiber membranes as well as evaluation of the impact of backwashing (using both air and water) on hollow fiber membrane integrity. The immersed hollow fiber membranes have been found to delaminate or crack in the area where the hollow fiber meets the potting material.

- The process of backwashing hollow fiber membranes may be responsible for the widening of the pores or the weakening of the material properties of hollow fiber membranes. To investigate the effects of backwashing on hollow fiber membrane performance and integrity, the structure-fluid model would be further modified to be able to evaluate the effects of air and water backwashing. Results from this model would again be compared to observations and measurements taken at the OCWD pilot- and demonstration-scale facility.

## 4.4. Task 2.4 – Investigate Salinity Removal Technologies

### 4.4.1. MWD Study

- Further research is needed to wed the high water production of NF membranes with the high salt rejection of RO membranes.
- Additional research to develop the next generation membranes that are chlorine tolerant to prevent biofouling or can exhibit unique surface charge characteristics to prevent particle and bacterial adhesion, or even scaling.
- A standardized protocol for interpreting RO membrane and water quality data to judge antiscalant effectiveness needs to be developed.
- Currently, NF membranes operate at significantly higher flux rates than RO membranes, but exhibit poorer salt rejection. Further research is needed to combine the high water production of NF membranes with the high salt rejection of RO membranes. .
- A primary concern with antiscalant testing is achieving representative water quality conditions that mimic those found in full-scale treatment plants at a given water recovery. Closed-loop membrane testing, while inexpensive, may not provide representative water quality conditions and single-pass, multi-array membrane systems are not only expensive but have high water flow rate demands (up to 20 gpm). Therefore, smaller, single-pass membrane test systems need to be developed.

### 4.4.2. OCWD Study

- Chlorine Tolerant Membranes – The successful development and widespread implementation of a new polymer membrane (chlorine tolerant) is a timely process. Since the CPTC membrane is still being developed, more testing would be required to determine the practicability of this membrane as an alternative to conventional TFC membranes for treating high fouling water and wastewater sources.
- Brine Disposal – It is recommended that the FBBR-GAC process be further investigated in laboratory scale as well as in pilot scale in order to assess its energy efficiency and cost-effectiveness. However, more investigation is needed in order to upgrade the process for better sulfate removal. Furthermore, detailed experimentation is needed to formulate a model that predicts simultaneous nitrate and sulfate removal in such systems.

- IMANS™ – It is necessary to study how other configurations of MF units could treat primary effluent. It will also be important to create dialogue between the regulatory agencies to discuss possible alternatives for reuse and discharge.

## 4.5. Task 2.5 – Investigate Disinfection Alternatives

### 4.5.1. MWD Study

- Future studies should be conducted to determine if *C. parvum* repair mechanisms may exist after UV treatment. Because of the similar disinfection achieved with different UV lamp types, future studies could be limited to one lamp type (such as the low-pressure UV lamp used in the *G. lamblia* studies reported here).
- To better quantify effects of organism repair in future studies, it would be beneficial to wait until improvements in *C. parvum* infectivity assays are made so that variability is reduced.
- Future research must complement the bench-scale data by evaluating the process efficiency and hydraulic characteristics of large-scale UV reactors. These evaluations should make recommendations for monitoring of transferred UV dosage and reporting of continuous disinfection effectiveness (i.e., on-line UV dosage measurement) so that drinking water treatment requirements can be met.

### 4.5.2. OCWD Study

*Evaluation of Wedeco-Ideal Horizons TAK 55 System*

- Wedeco-Ideal Horizons TAK 55 lamp technology is viable for meeting the disinfections standards set by the California Title 22 guidelines for wastewater reclamation. It is recommended that this system be considered for use in future or current municipal reclamation projects. For current installations this system can replace or enhance disinfection systems currently in place.

*Efficiency of UV for Protozoa Inactivation*

- Tests need to be run using G. muris as an indicator organism for evaluation on a pilot scale UV system without having to lower the transmittance to an unreasonable level. It is also necessary to find a way to keep the G. muris from sticking to the plastic batch tank and the plastic PVC pipes

*Evaluation of Pulsed UV*

- To test the pulsed UV 8″ diameter pilot unit on membrane treated wastewater. Several wastewater reclamation projects use membrane processes upstream of UV to improve the effectiveness of the pulsed UV system.

## 4.6. Task 2.6 – Investigate solid processing techniques

- Additional demonstration testing is needed to verify the results of previous testing including a focus on the thickening step assumptions used in this study
- Since capital costs are significant obstacles for F/T application. It is recommended that additional freezing systems be evaluated to determine if the capital costs can be reduced.

- For biological sludges, the BIOFREEZE™ system appears to be able to provide substantial benefits to anaerobic digestion. Further testing is needed to confirm that increased methane production can be achieved and to what extent dewaterability of the sludges can be expected.
- Brine reject is a growing concern nationwide as RO treatment of potable water increases. Future study should investigate the development of the BIOFREEZE™ system operating parameters and/or other freeze concentration technologies in order to optimize the FC process performance.

### 4.7. Task 2.7 – Perform energy and process assessment

It is recommended that the energy conservation measures (ECMs) identified in this project task be incorporated and used at other facilities throughout the state to further reduce the electrical demand and conserve our natural resources

### 4.8. Task 2.8 – Conduct Technology Transfer and Process Scale-Up for Commercial Deployment

#### 4.8.1. MWD Study

- It is recommended that this study be followed with research evaluating the effects of water quality and water treatment chemicals on UV disinfection and alternatives to microbial biodosimetry in characterizing UV reactor dose. Characterization of sensor readings to a known standard (i.e., radiometry) should also be continued.
- A second-generation 16-in. diameter element design should be developed and tested to eliminate the inefficiencies observed in the first prototype element and to help improve membrane productivity and fouling, which minimize both capital and O&M costs.
- An important issue that need to be addressed is the loading and unloading of the membranes. A dry 16-in.-diameter element weighs approximately 200 lbs and when wetted, an individual element can weigh over 300 lbs.

#### 4.8.2. OCWD Study

- Process recovery established here should be applicable to other future installations treating water with similar quality.
- The microfiltration membrane integrity also needs to be observed over a long-term period. It is recommended that continued testing using the cleaning procedure established during testing occur. Procedures established here could be easily modified for other installations where water qualities differ.
- Power requirements established during this testing should be further compared with those established elsewhere for MF processes as well as with other conventional treatment technologies such as chemical clarification or multi-media filtration

## 5.0 Project Summary Benefits to California

Significant benefits were derived from this study. The following is a summary of the major benefits to Californians as observed in the various tasks. A detailed discussion of these benefits can also be found in section 2 of this report.

### 5.1. Task 2.1 – Investigate Advanced Oxidation Processes

California utilities will benefit from this study in understanding the limitations of advanced treatment techniques such as UV disinfection before implementation. As UV radiation may provide excellent disinfection efficiency and low DBP formation at disinfection-level dosages, the higher energy requirements for treatment of micropollutants by UV systems may cause utilities to consider ozone as an alternative. Utilities, however, must also consider the level of DBPs that high ozone dosages would produce.

### 5.2. Task 2.2 – Investigate Biological Denitrification

Potable supply water is an emerging issue for most Californians, especially for Southern California where water demand significantly out-pacing available supply in recent years. Many local groundwater wells could be viable supply sources except for the nitrate contamination rendering the water not suitable for potable use. Biological denitrification offers California water utilities an option that is superior to conventional treatment schemes such as ion exchange, reverse osmosis, or electrodialysis. Each of these conventional technologies has significant disadvantages including: operation difficulty, large land requirement (chemical and waste handling), and high capital and O&M costs. When commercially deployed, biological denitrification will benefit Californians in: reduced need for import waters, energy conservation (reduced energy for water transport), and water conservation (use of contaminated local well water).

### 5.3. Task 2.3 – Investigate Solids Removal Technologies

#### 5.3.1. MWD Study

Results from this study will enable local municipalities to adopt desalination technologies to treat current and previously unusable potable water supplies. The primary economic benefit is the reduction of societal damages to the public and private sectors due to high salinity of Colorado River water. An additional benefit is the reduction of energy usage to reduce the TDS of CRW over currently available technologies. In addition, each acre-foot of CRW treated by technologies derived from this study would require less energy than current desalination practices, or through importing low salinity water from Northern California. Additionally, technologies evaluated during this project may be applicable to other source waters in California. These include municipal wastewater, brackish groundwater, and agricultural drainage water.

#### 5.3.2. OCWD Study

Preventing microporous fiber breakage will have a significant effect on water treatment and wastewater reclamation in California and throughout the world. The performance of reverse osmosis membranes in indirect potable reuse and the efficacy of disinfection processes (chlorination and ultraviolet irradiation) in direct non-potable reuse are directly dependent on MF and UF fiber integrity.

### 5.4. Task 2.4 – Investigate salinity removal technologies

#### 5.4.1. MWD Study

Results from this study, as well as other interrelated studies, will enable local municipalities to adopt desalination technologies to treat current and previously unusable potable water supplies. The primary economic benefit of the DRIP program is the reduction of societal damages to the public and private sectors due to high salinity of Colorado River water. An additional benefit is the reduction of energy usage to reduce the TDS of CRW over currently available technologies. Each acre-foot of CRW treated by technologies derived from this project would require less energy than current desalination practices, or through importing low salinity water from Northern California. Technologies evaluated during this project may be applicable to other source waters in California, including municipal wastewater, brackish groundwater, and agricultural drainage water.

#### 5.4.2. OCWD Study

*A. Chlorine Tolerant Membranes*

Developing non-traditional water sources for potable purposes require advanced water treatment facilities, which ultimately include membrane processes. The use of highly efficient, low fouling membranes would ultimately increase product water throughput while minimizing associated treatment costs. Using a lower pressure TFC membrane that exhibits fouling resistance would further reduce energy costs as well. Minimizing the occurrence of membrane biofouling through the use lower fouling, more efficient TFC membranes could ultimately result in significant energy savings for the California water producer already faced with looming power concerns.

*B. Brine Disposal*

The Fluidized Bed Biofilm Reactor with Granular Activated Carbon technology (FBBR-GAC has been proven to be very effective in the treatment of the RO brine concentrates. One notable advantage of fluidized bed reactors is that they require minimal space, and the reactor size is relatively smaller as compared to conventional techniques due to excessive biomass growth. The reaction time is short and the treatment efficiency is high, making it easily adoptable by the utilities planning to employ the RO technology to recycle water, in residential areas where land availability is scarce or limited.

*C. IMANS™*

This research and demonstration testing could significantly alter the manner in which wastewater agencies discharge into the ocean or any other water body. By evaluating the microfiltration process as a means of disposing primary effluent, alternate methods can help better mange waste discharges.

## 5.5. Task 2.5 – Investigate Disinfection Alternatives

### 5.5.1. MWD Study

UV disinfection is fast becoming a great benefit to California water treatment utilities. However, the recommendations stated above should be followed before implementing large-scale UV technology. Although the process shows to be viable at the bench-scale, large-scale technology with on-line monitoring capability are still in development and should be evaluated before implementing the technology as a reliable barrier to waterborne human disease and illness.

### 5.5.2. OCWD Study

- The testing done as part of this study could lead to certification of the Wedeco-Ideal Horizons TAK 55 technology by the California Department of Health Services for use in Title 22 reclamation applications. The certification of this technology leads to an increase in options for agencies in need of disinfection technologies for reclamation projects.
- Completing this task has also benefited California in that it shows that low levels of UV radiation are effective in disinfecting harmful protozoa. This allows other agencies to use UV technology in place of conventional disinfection technologies, which may be more expensive or may create unwanted disinfection byproducts
- The benefits to California from this project are that there is now evidence to show that pulsed UV technology can be applicable to disinfection for reclamation applications.

## 5.6. Task 2.6 – Investigate Solid Processing Techniques

The freeze-thaw process can be used to condition the biological residual before anaerobic digestion. The benefits to California from the use of this technology include:

- Increased methane generation capacity – methane recovery would enable plants to provide additional cogeneration capacity, thereby, reducing total electric system requirements statewide and increasing the quantity of power generated using "green methods".
- Increased dewaterability of sludge – additional volume reduction of wastewater residuals will reduce the landfill capacity needed for disposal of residuals and afford more landfill space in the state for municipal purposes.
- Reduce the amount of salt to be disposed in landfills – this will reduce the landfill capacity needed for disposal and afford more landfill space in the state.
- Reduce the amount of salt to be disposed by ocean discharge – this will reduce the risk of environmental degradation from ocean discharges of brine.
- Increase the dewaterability of water plant chemical residuals – additional volume reduction of residual will reduce the landfill capacity needed for disposal and afford more landfill space in the state.

## 5.7. Task 2.7 – Perform Energy and Process Assessment

The State of California benefits by the conservation of natural resources, reduction in pollution, minimized costs, and improved quality of treatment which thereby protects the environment.

Eleven energy conservation measures (ECMs) at the water plants and 12 at the wastewater plants were identified through this project. These ECMs are estimated to save 8,533,854 kWh annually, which produces a cost savings of approximately $564,580. Comparable benefits are expected at other water and wastewater treatment facilities throughout California if the same assessments are made there.

## 5.8. Task 2.8 – Process Scale-Up for Commercial Deployment

### 5.8.1. MWD Scale-up Study

UV treatment of drinking water could be a great benefit to California by allowing a relatively low-cost technology to provide enhanced disinfection and protection of public health. The development of large, 16-in. diameter elements will benefit the entire state of California by lowering the cost of desalination and reducing the energy requirements to treat brackish water. The successful development of these large-diameter elements will help to significantly lower cost of new, large-scale desalination facilities (greater than 100 mgd) by taking better advantage of economies of scale.

### 5.8.2. OCWD Scale-up Study

The benefits California is the establishment of microfiltration technology as a viable alternative for large-scale wastewater reclamation. The use of MF technology will allow reclamation to occur with greater ease and reduce California's dependence on imported water sources. The long-term benefit of this project is the credibility and confidence gained in this technology for future reclamation projects because of the success achieved through this testing. The space requirements established are very beneficial to other California municipal reclamation agencies. In most cases the land required for MF is several times smaller than that of current reclamation treatment processes. This testing has established a good estimate of the power requirements of MF technology for wastewater reclamation. The power requirement established during this testing will allow other agencies to evaluate the MF process for use in their treatment applications.

## 6.0 References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4. Orange County Water District, "Task 2.3 Report -- Solids Removal Technologies," Submitted to the California Energy Commission, February 2001

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### 6.5. Task 2.5

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### 6.7. Task 2.7

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### 6.8. Task 2.8

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Orange County Water District, “ Task 2.8 Report -- Scale up of a microfiltration system in municipal wastewater reclamation“, February 2001

## 7.0 Glossary

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|---|---|
| **AOP** | Advanced Oxidation Process |
| **Aerobic process** | A biological process that requires oxygen for microorganisms to flourish. |
| **Anaerobic process** | A biological process that requires the total absence of oxygen so that fermentation can occur. |
| **Anoxic process** | A biological process that requires the total absence of molecular oxygen. |
| **AWWARF** | American Water Works Association Research Foundation |
| **Backwashing** | The method used to clean filter media by reversing the water flow. |
| **BV** | Black & Veatch |
| **BOD** | Biochemical oxygen demand |
| **$BrO_3$** | Bromate |
| **B. subtilis** | Bacillus subtilis |

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| **CB** | Collimated beam, a beam in which the light rays travel parallel to each other, allowing for irradiation of samples under lab conditions without hydraulic disturbance. |
| **Clarifier** | A solids settling basin |
| **Coagulation** | The aggregation of colloidal and finely divided suspended matter |
| ***Cryptosporidium*** | A microorganism found in water supplies that causes a form of gastroenteritis. |
| **CA** | Cellulose acetate |
| **$CaCO_3$** | calcium carbonate |
| **CFU/mL** | colony forming units per milliliter |
| **cm** | centimeter |
| ***C. parvum*** | *Cryptosporidium parvum* |
| **CPTC** | Cyclopentanetetracarboxylic |
| **CRW** | Colorado River water |

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| **CMBR** | Completely-mixed batch reactor |
| **Commission** | California Energy Commission |
| **CSTR** | Continuously-stirred tank reactor |
| **Denitrification** | The chemical reduction of nitrate to gaseous nitrogen. This chemical process can be accomplished biologically using nitrifying bacteria. |
| **CWRC** | California Wastewater Reclamation Criteria |
| **Disinfection** | Destruction of disease causing microorganisms by physical or chemical means |
| **DAF** | Dissolved Air Flotation |
| **DHS** | Department of Health Services |
| **DNA** | Deoxyribonucleic acid |
| **DBP** | Disinfection byproduct |
| **DO** | Dissolved oxygen |

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| ***E. coli*** | *Escherichia coliform* |
| **ECM** | Energy Conservation Measure |
| **EDTA** | ethylenedinitrilo tetraacetic acid |
| **EDS** | Energy dispersive spectroscopy, a group of techniques used to analyze the atomic structure of materials |
| **EPRI** | Electric Power Research Institute |
| **Filter media** | The material through which water or wastewater is filtered. |
| **Filtration** | The process of passing a liquid through a filter to remove suspended solids. |
| **Floc** | Small jelly-like masses formed in a liquid by adding a coagulating chemical. |
| **Flocculation** | The collection of coagulated suspended solids into a mass by gentle stirring. |
| **Flux** | Permeate passing through the membrane per unit area per unit time. |

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| **Fouling** | The deposition of material such as colloidal matter, microorganisms, and metal oxides on the membrane surface or in its pores, causing a decrease in membrane performance. |
| **F/T** | Freeze Thaw |
| **FC** | Freeze Concentration |
| ***GC*** | Gas chromatography |
| $C_{12}H_{22}O$ | Geosmin, an earthy smelling chemical produced by certain blue-green algae and Actinomycetes. |
| **Giardia** | Group of single-celled, flagellated, pathogenic protozoans |
| ***G. muris*** | Giardia muris |
| **GAC** | Granular activated carbon |
| **GAP** | Green Acres Project |
| **GFD - Gallons per square foot per day** | Gpm - gallons per minute HAA - haloacetic acid |

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|---|---|
| **GWR System** | Groundwater Replenishment System |
| **HAA** | Haloacetic acid |
| **HVAC** | Heating, Ventilation, & Air Conditioning |
| **$ID_{50}$** | Dose that would infect 50 percent of the population inoculated |
| **Influent** | Water, wastewater, or other liquid flowing into a reservoir, basin, or treatment plant, or any unit thereof. |
| **Inorganic** | Chemical substances of mineral origin |
| **kW** | kilowatt |
| **kWh** | kilowatt-hour |
| **Membrane filter** | Technology used in water treatment for liquid-solids separation |
| **Metropolitan** | Metropolitan Water District of Southern California |
| **MF** | Microfiltration, a pressure driven membrane process that |

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| | feed stream by filtration. |
| **MS** | Mass spectrometry |
| **MCL** | Maximum contaminant level |
| **MDL** | Method detection level |
| **mg/L** | milligrams per liter |
| **mg/mL** | milligrams per milliliter |
| **mJ/cm$^2$** | millijoules per square centimeter |
| **mL** | milliliter |
| **mm** | millimeter |
| **MGD** | million gallons per day |
| **mW/cm$^2$** | milliwatts per square centimeter |
| **MPN** | most probable number |

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| **MIB** | 2-methylisoborneol, a musty-camphor-smelling chemical produced by blue-green algae and *Actinomycetes.* |
| **MPD** | m–phenylenediamine |
| **MTBE** | Methyl *t*-butyl ether, a common oxygenated gasoline additive. |
| **MRL** | Minimum reporting limit |
| **MS-2 coliphage** | A ribonucleic acid virus that can replicate only within its bacterial host, *Escherichia coli.* |
| **MTU** | Membrane test unit |
| **Nitrification** | The biological oxidation of ammonia to nitrate |
| **Nutrient** | An element that is essential for the growth of plants and animals |
| **NDMA** | N-nitrosodimethylamine ,a by-product of rocket fuel |
| **NA** | Not analyzed |

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| **ND** | Not detected |
| **NOM** | Natural organic matter, a heterogeneous mixture of organic matter that occurs ubiquitously in both surface water and groundwater. |
| **Normalized flux** | The permeate flow rate through the membrane adjusted to constant operating conditions. |
| **NPW** | Non-Potable Water |
| **NTU** | Nephelometric Turbidity Units |
| **OCWD** | Orange County Water District |
| **OCSD** | Orange County Sanitation Districts |
| **Organic** | Chemical substances of animal or vegetable origin |
| **$O_3$** | Ozone |
| **$ClO_4^-$** | Perchlorate, used in the manufacturing of solid rocket fuels & explosives |
| **PEROXONE** | Combination of ozone and hydrogen peroxide |

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| **Photolysis** | Chemical decomposition that is driven by photons of sunlight or UV light |
| **PA** | Polyamide PFU/mL - plaque forming units per milliliter |
| **PIER** | Public Interest Energy Research |
| **PFU/ mL** | Plaque forming units per milliliter |
| **Pulsed UV** | Ultraviolet light generated in a wave form at a specific frequency. |
| **RNA** | Ribonucleic acid |
| **RO** | Reverse osmosis, a pressure-driven membrane separation process that removes ions, salts, and other dissolved solids and nonvolatile organics. |
| **Scale** | Coating or precipitate deposited on surfaces |
| **SEM** | Scanning electron microscopy |
| **SDI** | Silt density index, an empirical measure of the plugging characteristics of membrane feed water |

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| **Specific flux** | Permeate (water) flux divided by the net driving pressure. |
| **SPW** | State Project water |
| **SST** | Separation Systems Technology, Inc. |
| **Turbidity** | Murkiness in water caused by suspended matter |
| **T&O** | Taste and odor |
| **TFC** | Thin film composite |
| **THM** | Trihalomethane, derivatives of methane ($CH_4$) |
| **TMC** | Trimesoyl chloride |
| **TMP** | Trans-membrane pressure, the net pressure loss across the membrane |
| **TDS** | Total Dissolved Solids |
| **TOC** | Total organic carbon |

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| **TWAS** | Thickened Waste Activated Sludge |
| **USEPA** | United States Environmental Protection Agency |
| **UV** | Ultraviolet light |
| **μg/L** | micrograms per liter |
| **μL** | microliter |
| **μm** | micrometer |
| **VOC** | Volatile organic compound |
| **WF 21** | Water Factory 21 |

# Appendix I

Appendix I: Task 2.1: Report by MWD on Advanced Oxidation Processes

# Appendix II

Appendix II: Task 2.2: Report by EPRI on Biological Denitrification

# Appendix III

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| Appendix IIIa: | Task 2.3 A: Report by MWD on Solids Removal Technologies |
| Appendix IIIb: | Task 2.3 B: Report by Univ. of Nevada, Reno on Preventing Membrane Fiber Breakage |

# Appendix IV

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| Appendix IVa: | Task 2.4 A: Report by MWD on Salinity Removal Technologies |
| Appendix IVb1: | Task 2.4 B1: Report by OCWD on Salinity Removal Technologies |
| Appendix IVcb2 | Task 2.4 B2: Report by Univ. of So. Calif.(USC) on Denitrification of Brine |
| Appendix IVdb3: | Task 2.4 B3: Report by Carollo Engineers, USC and OCWD on Salinity Removal Tech. |

# Appendix V

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| Appendix Va: | Task 2.5 A: Report by MWD on Disinfection Alternatives |
| Appendix Vb: | Task 2.5 B: Report by OCWD on Disinfection Alternatives |

# Appendix VI

Appendix VI: Task 2.6 Report by EPRI on Solids Processing Technologies

## Appendix VII

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| Appendix VII: | Task 2.7 Report by EPRI on Water & Wastewater Treatment Plant Energy Optimization |
| Appendix VIIa: | Task 2.7 A: Report by HDR on Vallejo Sanitation and Flood Control District Energy Audit |
| Appendix VIIb: | Task 2.7 B: Report by EPRI on Harry Tracy WTP and Baden Pumping Station Energy Audit |
| Appendix VIIc: | Task 2.7 C: Report by EPRI on Union Sanitation Dist. Wastewater Treatment Energy Audit |

# Appendix VIII

Appendix VIIIa: Task 2.8 A: Report by MWD on Scale-up Issues for UV Disinfection and RO Desalination

Appendix VIIIb: Task 2.8 B: Report by OCWD on Scale-p Issues for a Microfiltration System

Appendix VIIIc: Task 2.8 C: Report by EPRI on Technology Transfer